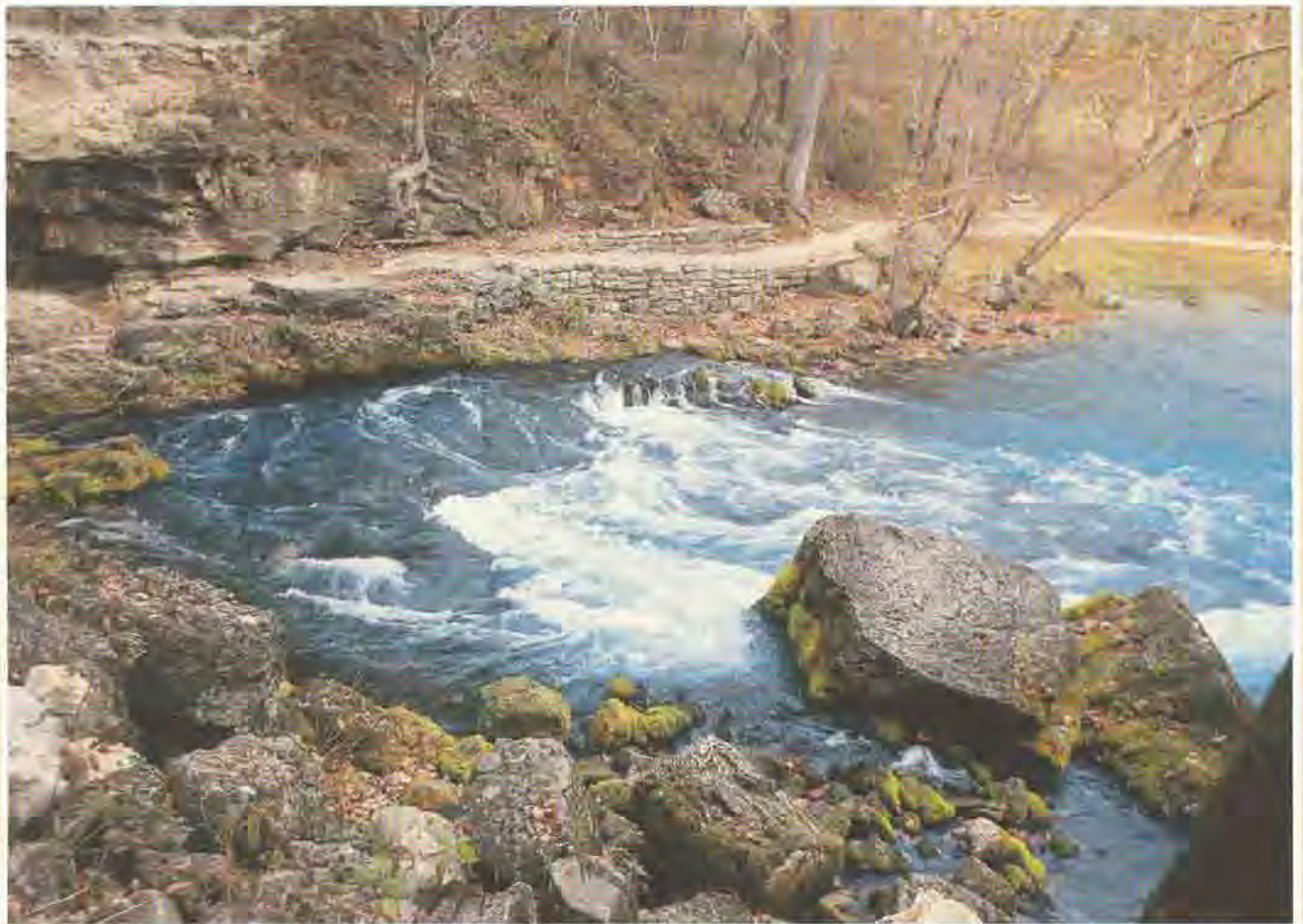


Water Resources Report Number 46
MISSOURI STATE WATER PLAN SERIES
VOLUME II

Groundwater Resources of Missouri



MISSOURI DEPARTMENT OF NATURAL RESOURCES
Division of Geology and Land Survey

COVER:

Big Spring, a few miles south of Van Buren in Carter County, is Missouri's largest spring. On an average day it feeds nearly 290 million gallons of high-quality groundwater into the Current River. Photo by Jim Vandike.

Missouri State Water Plan Series Volume II

Groundwater Resources of Missouri

by
Don E. Miller
and
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PREFACE

MISSOURI STATE WATER PLAN TECHNICAL VOLUME SERIES

The Missouri Department of Natural Resources State Water Plan Technical Volume Series is part of a comprehensive state water resource plan. This portion is designed to provide basic scientific and background information on the water resources of the state. The information in these technical volumes will provide a firm foundation for addressing present and future water resource needs and issues. Each volume in the series deals with a specific water resource component.

Volume I

The *Surface Water Resources of Missouri* contains a basin-by-basin assessment of Missouri's surface water resources. It discusses the effects of climate, geology and other factors on the hydrologic characteristics of major lakes, streams and rivers. It also assesses surface-water availability and development in the state.

Volume II

The *Groundwater Resources of Missouri* presents information on the availability and natural quality of groundwater throughout the state. It focuses on Missouri's seven groundwater provinces and includes their geology, hydrogeology, areal extent, general water quality, and potential for con-

tamination. Aquifer storage estimates are given for each aquifer and county. The report also reviews the different types of water-supply wells in use and how water well construction techniques vary between areas and aquifers.

Volume III

Missouri Water Quality Assessment focuses on the current quality of Missouri surface water and groundwater. The volume looks at chemical, bacteriological and radiological water-quality, and natural and man-induced water-quality changes.

Volume IV

The *Water Use of Missouri* describes how Missouri is presently using its surface-water and groundwater resources. The report covers private and public water supplies, industrial and agricultural water uses, and water use for electrical power production, navigation, recreation, fish and wildlife.

Volume V

Hydrologic Extremes in Missouri: Flood and Drought provides basic information about flood and drought specific to Missouri. A historical perspective is given, as well as information that can be used in planning for hydrologic extremes. It also describes concepts and defines terminology helpful in understanding flood and drought.

Volume VI

Water Resource Sharing - The Realities of Interstate Rivers presents Missouri's views concerning interstate rivers. Because of its location, Missouri can be greatly affected by activities and water policy in the upper basin states of the Missouri and Mississippi river basins. Missouri policy can also affect downstream states on the Mississippi, Arkansas and White rivers. Many serious

issues affecting these rivers have less to do with their physical characteristics than with political, economic and social trends.

Volume VII

Missouri Water Law provides an overview of the laws that affect the protection and use of Missouri's water resources. It supplies reference information about existing doctrines, statutes and case law.

EXECUTIVE SUMMARY

Missouri has an outstanding groundwater resource base and it is one of the state's most precious natural resources. There are more than a dozen major aquifers in Missouri with depths that vary from a few feet below land surface to more than 2,000 feet. Their areal extents range from a few hundred square miles for localized channel sandstone deposits, to that of the Ozark aquifer, which underlies more than 35,000 square miles of southern Missouri.

To assess Missouri's groundwater resources, the state has been divided into seven major groundwater provinces and two subprovinces. The boundaries are based on aquifer area, type of groundwater system, groundwater flow patterns, groundwater quality, and other factors.

Major groundwater provinces include the St. Francois Mountains, the Salem Plateau, the Springfield Plateau, Southeastern Lowlands, Northwestern Missouri, Northeastern Missouri, and West-Central Missouri. The Mississippi River alluvium and the Missouri River alluvium are treated as subprovinces.

Most Missouri groundwater originated as, and is replenished by, precipitation. Shallow aquifers separated from the land surface by only a few feet of relatively permeable materials receive considerable recharge very quickly after precipitation occurs. Deeper aquifers that are overlain by low-permeability strata, or aquitards, are generally recharged much more slowly. Groundwater recharge rates vary widely, from less than an inch per year in parts of northern and west-central Missouri, to more than 12 inches in certain karst areas in southeastern Missouri.

Missouri's greatest groundwater resources lie south of the Missouri River. The Salem Plateau groundwater province contains the best groundwater resources. Thick dolomite and sandstone formations of Cambrian and Ordovician age underlie the area, and comprise the Ozark and St. Francois aquifers. The Missouri River alluvial aquifer lying south of the river is also included in this province. In the Salem Plateau groundwater province, these aquifers contain approximately 233 trillion gallons, or about 46.6 percent of the usable groundwater in the state. The St. Francois and Ozark aquifers extend to the west into the Springfield Plateau groundwater province, where they are overlain by several hundred feet of Mississippian-age limestones that comprise the Springfield Plateau aquifer. Groundwater storage in this province is estimated to be about 122.5 trillion gallons, or about 24.5 percent of the usable groundwater in Missouri.

Considering its size, the Southeastern Lowlands groundwater province contains the greatest volume of groundwater per unit area. Parts of the St. Francois and Ozark aquifers are usable in the northwestern part of this province. However, most of the usable groundwater is contained in thick deposits of shallow alluvium and deeper Tertiary- and Cretaceous-age sands. About 15.2 percent of the state's groundwater, an estimated 75.8 trillion gallons, is found in this southeastern corner of Missouri.

The remaining groundwater provinces south of the Missouri River contain more modest reserves of usable groundwater. In the St.

Francois Mountains groundwater province, the St. Francois aquifer is typically the only source of appreciable quantities of groundwater. Much of the area is directly underlain by Precambrian-age igneous rocks that are essentially impermeable, and that store or yield very little water. This area contains less than 0.2 percent of Missouri's groundwater, which is an estimated 919 billion gallons.

The West-Central Missouri groundwater province fares somewhat better. The freshwater-salinewater transition zone forms the boundary between the Springfield Plateau and West-Central Missouri groundwater provinces. Aquifers in Mississippian-, Ordovician-, and Cambrian-age rock south of this transition zone yield good-quality water, but the same aquifers north of the transition zone contain highly mineralized water. The northern part of this province borders the Missouri River and includes the Missouri River alluvium. Buried alluvial and glacial drift channels paralleling the river help to locally increase its groundwater resource base. Most of the area is underlain by low-permeability Pennsylvanian-age sedimentary strata that yield, at best, only meager volumes of marginal quality water. Groundwater storage estimates for this region are about 1.2 trillion gallons, or about 0.24 percent of the usable groundwater in Missouri. Cumulatively, the groundwater provinces south of the Missouri River contain about 86.7 percent of the states usable groundwater.

The remaining 13.3 percent of Missouri's potable groundwater occurs in the northern part of the state. In the Northwestern Missouri groundwater province, thick glacial materials and alluvial deposits along the Missouri River form the most significant aquifers. This area contains an estimated 10.9 trillion gallons of groundwater, or about 2.2 percent of the groundwater in Missouri. Deeper bedrock aquifers contain vast quantities of water, but the water is too highly mineralized to be considered potable.

Groundwater resources in the Northeastern Missouri groundwater province are much more varied. Glacial drift also underlies much

of this area, but it is generally thinner and finer-grained than in northwest Missouri. Alluvial deposits bordering the Missouri and Mississippi rivers are important aquifers. Mississippian-age limestones yield modest amounts of marginal quality water in the northern part of the region, while south of the freshwater-salinewater transition zone, Mississippian, Ordovician, and Cambrian limestones, dolomites, and sandstones are important aquifers. This province contains about 11.2 percent of Missouri's potable groundwater, a volume of about 55.8 trillion gallons.

Statewide groundwater storage estimates show that aquifers in Missouri contain slightly more than 500 trillion gallons of usable-quality groundwater. This volume of water would cover the state to a depth of over 34 feet, or supply each of its 5.1 million residents 100 gallons of water per day for nearly 2,700 years. It is equivalent to the volume of rainfall that Missouri normally receives in nearly an 11-year period.

The volume of groundwater that Missouri has available is so staggering that it is difficult to imagine how such a resource could ever be depleted. In a few areas of the state it would be exceedingly difficult to use all of the available groundwater. However, groundwater resources are not evenly distributed across the state; neither is groundwater use. Production from a particular aquifer may be minimal throughout most of a county, but very high in an area of only a few square miles due to municipal, industrial or agricultural needs. It is quite possible to overuse an aquifer in one area, while the same aquifer a few miles away is essentially unused.

If groundwater resources were evenly distributed across the state, then each square mile of Missouri would contain about 7.17 billion gallons of water beneath it. Unfortunately, this is not the case. Average groundwater availability in Missouri north of the Missouri River is only about 3 billion gallons per square mile, while that of the southern part is much higher, about 9.4 billion gallons per square mile. Locally, groundwater storage in north-

ern Missouri can be much less than the average. Thus, a resource that many take for granted in the southern part of the state is considered a precious commodity in the north.

Ideally, the volume of water in Missouri aquifers should be kept relatively constant. If more water is removed from the aquifer than is replenished by recharge, groundwater levels begin to decline. As depth to groundwater increases, the costs of well construction, well deepening, and pumping all increase accordingly. The safe yield of an aquifer is the amount of water that can be withdrawn from it without producing an undesired result, such as the intrusion of poor-quality water and greatly increased pumping costs. Aquifer withdrawals that exceed the safe yield of the aquifer can cause problems ranging from local, minor drawdown or water-quality changes, to serious water-level decline problems including dewatering of existing wells. Alternative water sources should be explored and used where groundwater use exceeds the safe yield of an aquifer.

A sizeable percentage of Missouri's usable groundwater is in aquifers that are relatively expensive to exploit. For example, the St. Francois aquifer in the St. Francois Mountains area is fairly shallow. However, in

southwestern Missouri it may be more than 2,000 ft below land surface. So, even though it is considered a groundwater resource, it is mostly unused because shallower, more productive aquifers are available throughout much of the Ozarks.

Another factor to consider is that the quality of water is very important in determining its potential use. Groundwater contamination due to improper waste disposal, inappropriate land use, accidental spills of potential contaminants, and other factors can cause a usable aquifer to essentially become unusable, at least for an extended period of time.

Although groundwater is a vast resource in Missouri, it is also a finite resource. Unlike many western states where groundwater recharge rates are so low that groundwater is not replenished, most Missouri aquifers receive considerable recharge in most years. With proper management and protection, Missouri's groundwater resources can continue to provide high-quality water to meet many of the states domestic, municipal, industrial, agricultural, and recreational needs. Avoiding aquifer over-use and protecting groundwater from contaminants are two ways to best ensure its continued availability for future generations.

INTRODUCTION

Hidden beneath the varied landscapes of Missouri is one of the state's most treasured and important natural resources. It's neither coal, petroleum, nor natural gas, which are three natural resources that are certainly important and have brought wealth to many people. Nor is it minerals, though they too are an important economic benefit to Missouri. This hidden treasure is water, and to be more specific, groundwater.

Missouri's water resource base is divided into surface water and groundwater. As the name implies, surface water is water that is found on the Earth's surface. It is the water flowing in rivers and streams and impounded in lakes and ponds. (For more information on Missouri's surface-water resources, see *Surface Water Resources of Missouri, Missouri State Water Plan, Volume I*.) Groundwater is water that occurs beneath the Earth's surface. It is ultimately supplied and replenished by precipitation that finds its way into the subsurface where it moves through and is stored in bedrock and other earth materials. Geologic units that can store and release significant quantities of water are called *aquifers*. Many aquifers exist in Missouri.

People need many things in order to thrive, but basic survival requires oxygen, food, and water. Oxygen, of course, is the most immediate concern; without it a human will quickly perish. Food is a far less pressing matter. Although the stomach may protest loudly, healthy individuals have been known to live for several weeks without nourishment. One cannot survive that long without water. Depending upon temperature, exer-

tion and other factors, humans need between two quarts and a gallon of drinking water each day. At most a person can survive only a few days without water.

Although man can survive on a gallon of water per day, society can't. In reality, the amount of water necessary for survival is but a tiny fraction of the amount of water needed to support a society such as ours. A modern household can be operated with as little as 40 gallons of water per day per capita (gpdc). More realistically, the average household uses closer to 100 gpdc for domestic needs. When commerce, industry, power generation and other components of society are added, per capita water needs jump to more than a thousand gallons of water per day per person.

Missouri occupies an area of about 69,709 square miles, and the geologic conditions across the state vary greatly. There are more than a dozen major aquifers underlying various parts of the state. In some areas, three or more aquifers are present. In other areas, where groundwater resources are poor, there may be just one aquifer or none at all.

To assess Missouri's groundwater resources, the state has been divided into seven major groundwater provinces. These provinces include the St. Francois Mountains, Salem Plateau, Springfield Plateau, Southeastern Lowlands, Northwestern Missouri, Northeastern Missouri, and West-Central Missouri. An eighth area—the Missouri and Mississippi river alluvial aquifers—was evaluated separately. However, county and groundwater province storage estimates include the Missouri-Mississippi alluvial aquifer water that is within each respective area.

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PHYSIOGRAPHY

Missouri is located in the midcontinent of the United States and is bounded by the states of Iowa on the north, Nebraska, Kansas and Oklahoma on the west, Arkansas on the south,

Illinois on the east, and Tennessee and Kentucky on the southeast (figure 1). The state is divided into 114 counties; the city of St. Louis is not considered to be a part of any county and is not counted as a county.

The state is drained by three major river systems—the Missouri River, which forms the western boundary of the state from the Iowa line to Kansas City, the Mississippi River, which forms most of the eastern boundary of the state, and the Arkansas River, which drains the south-western corner of the state.

The United States is divided into 34 regions called physiographic provinces, which are grouped into major divisions. These provinces are described primarily on the basis of their geologic structure, distinctive landforms, climate, vegetation, soils, water, and other



Figure 1. Missouri and surrounding states.

factors. The boundaries between the provinces are generally distinctive, and show the structural or geologic differences.

Missouri is located within three major physiographic divisions—the Atlantic Plain, the Interior Plains, and the Interior Highlands. All of these are large regions that contain parts of several states. The part of Missouri within the Atlantic Plain is the southeastern corner of the state, which is commonly called the Bootheel. Here, the Atlantic Plain division has been further subdivided with Missouri placed into the Southeastern Lowlands subprovince of the Coastal Plain physiographic province (figure 2).

Much of northern and western Missouri is within the Interior Plains division. The part of

this division that lies in northern Missouri is within the Dissected Till Plains subprovince of the Central Lowlands physiographic province. The part of western Missouri within the Interior Plains is the Osage Plains subprovince of the Great Plains physiographic province.

The remainder of Missouri is in the Ozark Plateau physiographic province of the Interior Highlands major division. The Ozark Plateau is further subdivided into the Springfield Plateau, the Salem Plateau and the St. Francois Mountains.

The physiographic regions discussed in this report will be the smallest subdivisions—the Dissected Till Plains, Osage Plains, Springfield Plateau, Salem Plateau, St. Francois Mountains and Southeastern Lowlands.

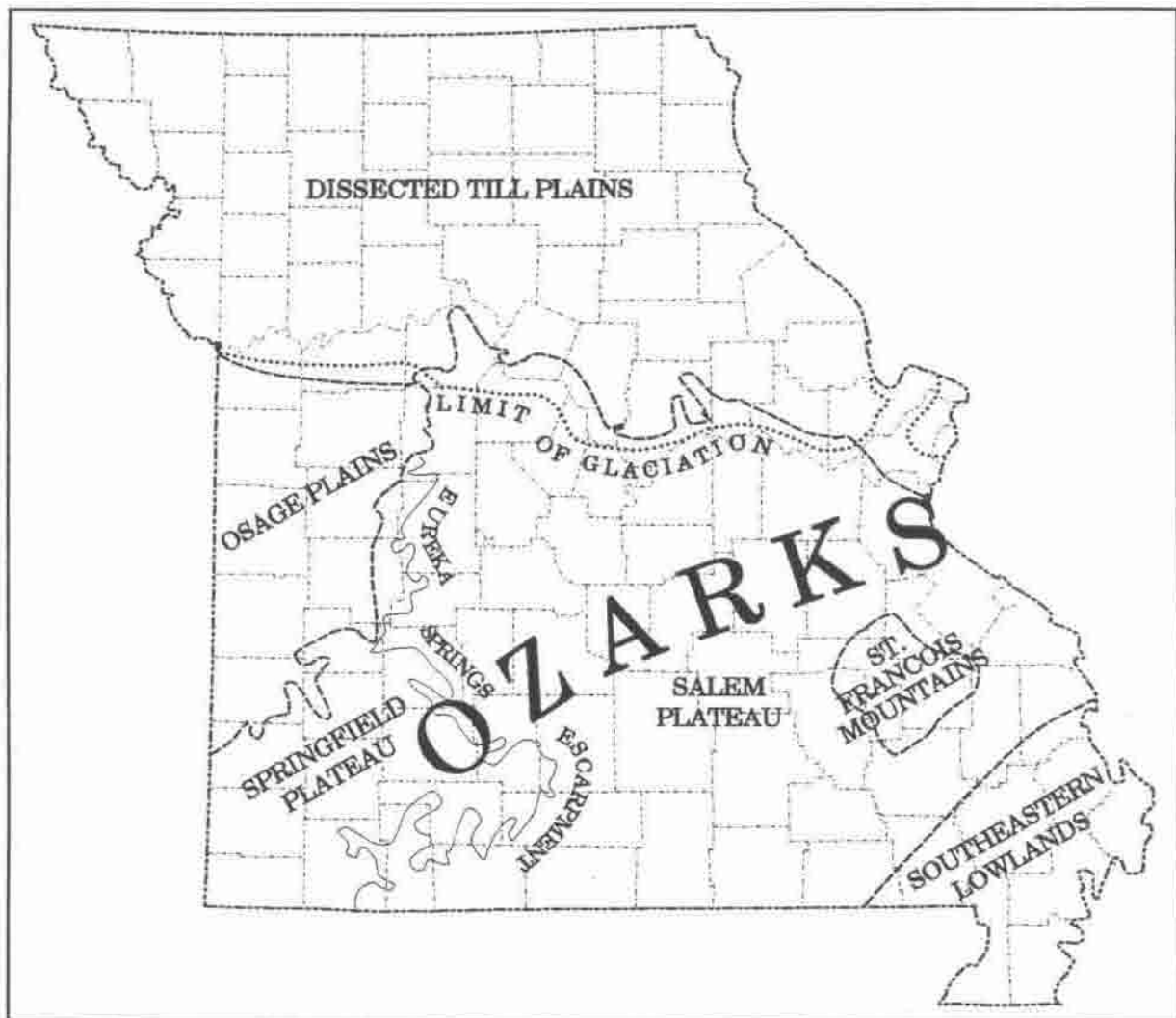


Figure 2. Map showing physiographic regions and features of Missouri.

GEOLOGIC OVERVIEW OF MISSOURI

The geology of Missouri is more complex and varied than is often expected for a state in the midcontinent region. Bedrock formations underlying the state range in age from Precambrian to Tertiary, and the unconsolidated deposits range in age from Cretaceous through Recent. There is a marked difference in rock type throughout the geologic section.

The oldest rocks exposed in Missouri are the Precambrian igneous rocks in the St. Francois Mountains in southeastern Missouri. The St. Francois Mountains form the core of the Ozark Uplift. Here, the eroded subdued remnants of Precambrian-age mountains are surrounded by younger marine sedimentary rocks. Cambrian- and younger Paleozoic sedimentary rocks were deposited on top of the Precambrian bedrock surface across the state. Deposition was not continuous throughout geologic time. The rock column is marked in several places by gaps in the record. These hiatuses of either nondeposition, or deposition followed by erosion, are mostly related to world-wide sea level changes or continental uplift or downwarping.

Mississippian-, Pennsylvanian-, and possibly Devonian-age sedimentary rocks were originally widespread across Missouri, but have been mostly removed by erosion throughout the Ozark region. Today, Mississippian rocks crop out mostly in the Springfield Plateau of southwestern Missouri, in central Missouri and in a small part of northeastern Missouri along the Lincoln Fold.

Rocks younger than Pennsylvanian-age occur in Missouri in only a few places, primarily in the Southeastern Lowlands. Here,

several thousand feet of sands and clays were deposited during the Cretaceous and Tertiary periods. During the Pleistocene epoch, or Ice Age, continental ice sheets advanced and retreated across northern Missouri. The southern extent of glaciation roughly parallels the Missouri River in Missouri. Unconsolidated deposits left by the glaciers consist of clay, silt, sand, gravel and even boulders that were derived from the physical and chemical weathering of older rock units to the north. In most places, the glacial deposits are unsorted. In some places, however, sediments were deposited by water, particularly in drift-filled preglacial channels.

During more recent times, over-bank flooding of present day rivers has left deposits of alluvium on river floodplains. The alluvium of the larger rivers, such as the Missouri and Mississippi, generally consists of clay, silt and fine sand in the shallower zones, and increasingly coarser sand and gravel in the deeper zones. The same alluvial deposits are found throughout most of the Southeastern Lowlands where the paths of the Mississippi, Ohio and St. Francis rivers have meandered.

Table 1 is a generalized geologic section of Missouri showing the age, rock type, special features, and general water-bearing characteristics of the geologic formations in Missouri. Figure 3 is a generalized geologic map of Missouri showing the distribution of the rocks discussed in the geologic section. The geologic map shows a roughly concentric distribution of rock formations centered around the St. Francois Mountains in the southeastern part of the state. The St. Francois Mountains

are eroded remnants of much older igneous mountains that exist today as knobs or hills. These hills or knobs were emergent islands when younger sedimentary rocks were being deposited in inland seas. The concentric pattern developed as subsequent, gentle and intermittent uplift occurred along the Ozark dome.

The Ozark dome or Uplift is a broad, asymmetrical arch (McCracken, 1971) whose eastern and southeastern sides dip or tilt more steeply, while the northern and western sides have a rather gentle dip. The axis of the uplift trends from the St. Francois Mountains to the southwestern part of the state. As erosion occurred, vast quantities of rock material were eroded away, and a radial drainage pattern developed. The Precambrian igneous and metamorphic rocks at the core of the uplift were exposed, leaving sediment-filled basins between them, and all other, younger rocks dipping or tilted away from them. As a result, rocks that are at the surface around the St. Francois Mountains are found several thousand feet below the surface in northern and western Missouri.

Much of the subsurface geologic information available today is from studying samples of rock cuttings from water wells, mineral test holes, and oil and gas wells. Water well drillers typically save a small quantity of cuttings from each 5-foot interval of the well. The samples are processed by the Department of Natural Resources' (DNR) Division of Geology and Land Survey (DGLS) technicians, and studied microscopically by geologists who prepare a geologic log of each well that is studied. Routinely, companies drilling wells to test for minerals or oil use a core drill to collect rock cores in the zones of interest. The cores are cylindrical samples of rock that can be studied in much greater detail than the cuttings. To a trained observer, however, both rock core and cuttings are valuable data sources. As a service to Missouri citizens, the Division of Geology and Land Survey maintains a large collection of rock cores at the McCracken Core Library, and rock cuttings at the Land Survey building. Currently, the collection contains

cuttings from more than 30,000 wells and about 1.8 million feet of rock core.

Missouri geologists recognized in the early 1900s that the identification of individual Cambrian and Ordovician formations from drill cuttings was extremely difficult. All of the samples had lithological similarities which made the identification of individual formations almost impossible. However, it was noted that the insoluble (non-carbonate) part of the sample could be used to identify particular zones and formations. From this, a technique of well logging called the *insoluble residue method* was developed. This system recognizes that each geologic horizon has unique assemblages of materials, usually silicious, which characterize it. Sample preparation involves dissolving the carbonate fraction of the sample with hydrochloric acid. The insoluble remainder, which includes chert, silica sand, metallic minerals, and other secondary materials, is examined microscopically. Over a period of many years, using insoluble residues, geologists developed a system to identify geologic formations using sequences of certain residue types. Using this method, it is possible not only to determine from which geologic formation the samples came, but also what region of the state.

Figure 4 shows a simplified version of an insoluble residue log that was prepared from drill cuttings collected from city of Rolla municipal well #14. The notations on the left side of the original strip log (not shown on figure 4) show the residue types identified by the geologist who logged the well. Each line on the sample log marks a five-foot interval. The color (or in the case shown here the pattern) inside the rectangles depicts the relative amounts of each mineral in the sample. In this way, a person studying the log can determine the percentage of constituents for that five-foot interval. The formation boundaries and names are indicated at the extreme left margin. The well log files at the Division of Geology and Land Survey contain more than 25,000 insoluble residue logs from mineral test wells, oil and gas wells, and water supply wells.

System	Series	Group	Geologic Unit	Hydrologic Unit
Quaternary	Holocene		Alluvium	Missouri and Mississippi rivers and in Mississippi embayment, 500-2,000 gpm. Yields are less along smaller rivers.
	Pleistocene		Loess, till, and other drift, sand and gravel	Drift and till typically yield 0-5 gpm. Drift-filled preglacial valleys typically yield 50-500 gpm.
Tertiary	(undifferentiated)			Wilcox Group (Mississippi embayment only), 50-400 gpm.
Cretaceous	(undifferentiated)			McNairy Formation (Mississippi embayment only), 200-500 gpm
Pennsylvanian	(undifferentiated)			Northern and west-central Missouri, 1-20 gpm, regionally forms a confining layer.
Mississippian	Chesterian		(undifferentiated)	Springfield Plateau aquifer in Southwest Missouri. Mississippian aquifer in central and east Missouri. Post-Maquoketa aquifer in the St. Louis area.
	Meramecian		(undifferentiated)	
	Osagean		Keokuk Limestone Burlington Limestone Elsey Formation Reeds Spring Formation Pierson Limestone	5-30 gpm.
	Kinderhookian	Chouteau	Northview Formation Sedalia Formation Compton Limestone	Ozark confining unit
			Hannibal Formation	
Devonian	(undifferentiated)			
Silurian	(undifferentiated)			
Ordovician	Cincinnatian	Maquoketa	Orchard Creek Shale Thebes Sandstone Maquoketa Shale Cape Limestone	Ozark aquifer (upper) Yield is greatest from St. Peter Sandstone. Yields of 5 to 50 gpm are possible.
	Mohawkian	Decorah	Kimmswick Limestone (three formations) Plattin Limestone Joachim Dolomite Dutchtown Formation St. Peter Sandstone Everton Formation	
	Whiterockian			
	Canadian		Smithville Formation Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Gunter Sandstone Member	Ozark aquifer (lower) Yields vary greatly with location and well depth. In Salem Plateau, yields are typically 50-500 gpm. In Springfield Plateau and central Missouri, yields are typically 500 to 1,200 gpm.
Cambrian	Croixian		Eminence Dolomite Potosi Dolomite	St. Francois confining unit. St. Francois aquifer. Yields of 10 to 100 gpm are possible.
		Elvins	Derby-Doerun Dolomite Davis Formation	
			Bonneterre Formation Lamotte Sandstone	
Precambrian	(undifferentiated)		Igneous, metasediments, and other metamorphic rock.	Not a significant aquifer

[The stratigraphic nomenclature used in this report is that of the Missouri Department of Natural Resources, Division of Geology and Land Survey modified after Koenig (1961.)]

Table 1. Generalized section of geologic and stratigraphic units (from Vandike, 1993).

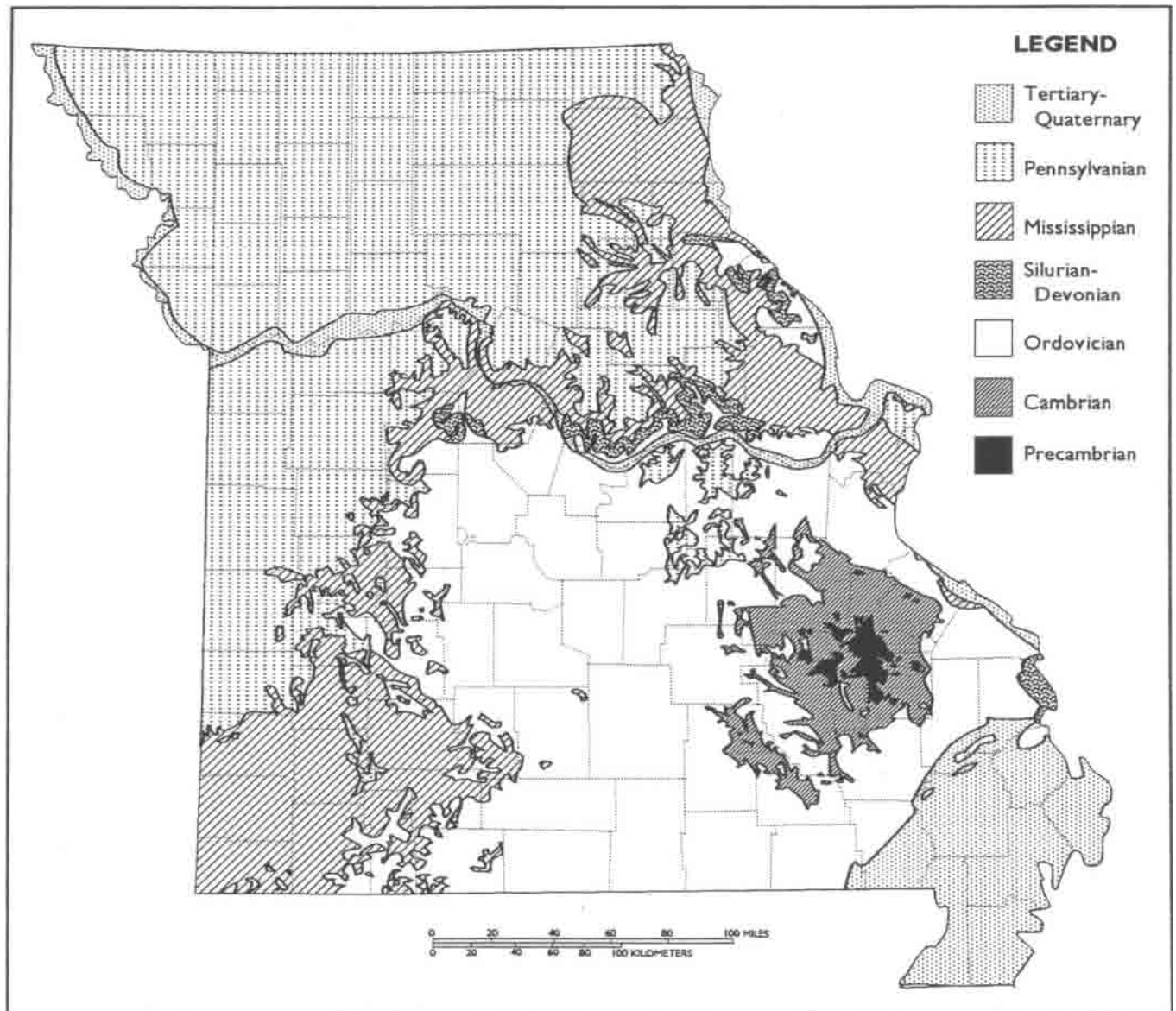


Figure 3. Generalized geologic map of Missouri.

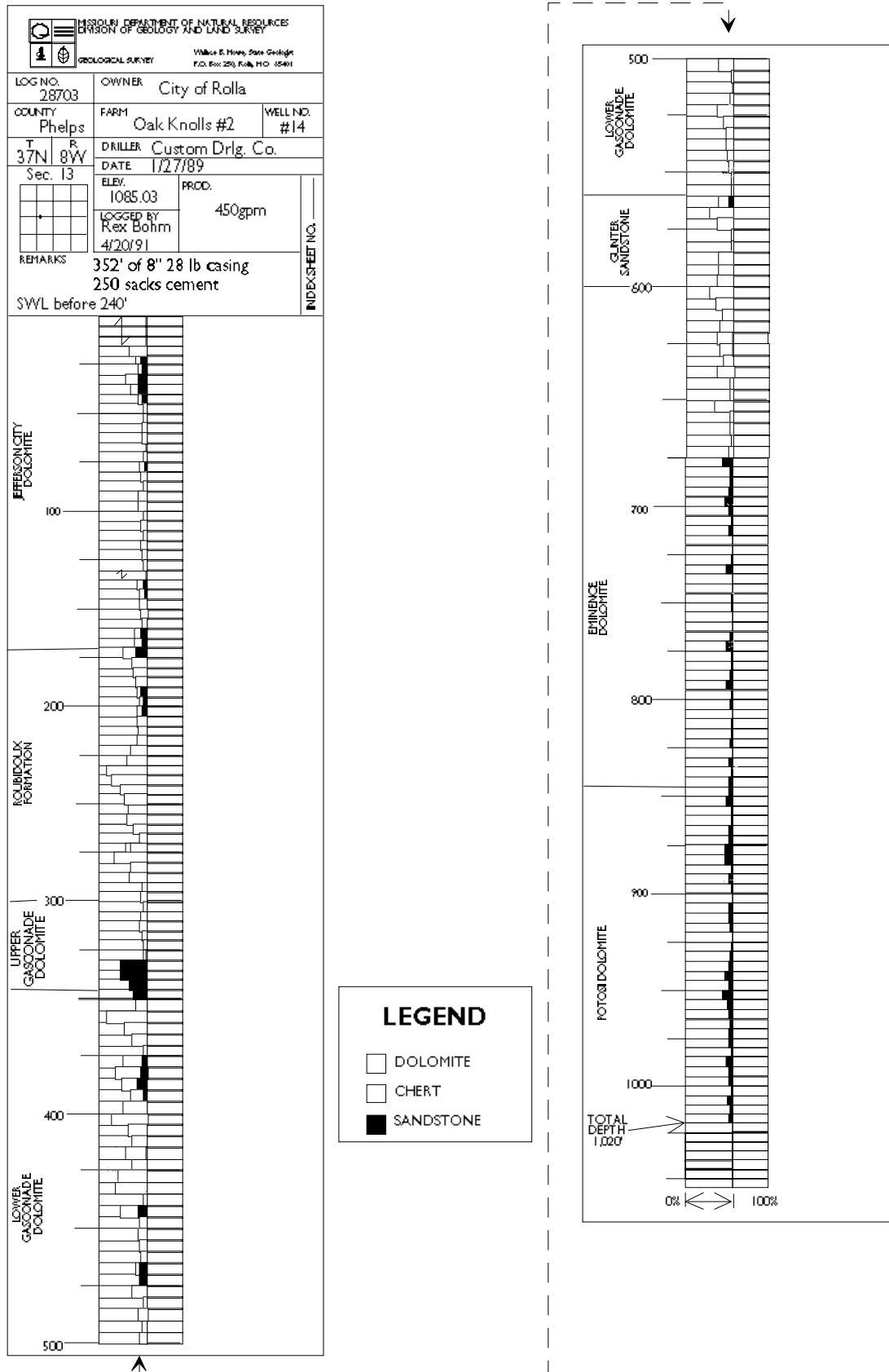


Figure 4. Insoluble residue log of Rolla city well #14.

GENERAL HYDROGEOLOGY

Groundwater is contained in and moves through aquifers. Various definitions exist for the term aquifer, but generally an aquifer is defined as a saturated, permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients. Nearly all of the geologic formations in Missouri are capable of storing and discharging varying amounts of groundwater. However, not all of the units yield water in sufficient quantities to be considered important aquifers. The distinction between an important aquifer and one which is not is often subjective, and to a great extent depends on location and perspective. A rural resident living in northwestern Missouri might be pleased to have a well that yields one to three gallons per minute (gpm). Since groundwater resources are generally poor in this area, and yields greater than this are uncommon, such a yield would be considered good by local standards. Another person living in central Missouri, where well yields are generally better, would likely be disappointed if his well yielded less than 15 gpm. For an irrigation system, public water supply, or an industry requiring substantial water, any quantity less than several hundred gallons per minute may not be considered significant.

AQUIFER PARAMETERS

Aquifers can be classified into two general types, *unconfined aquifers* and *confined aquifers*. In an unconfined or water table aquifer, the *water table* forms the upper

boundary of the aquifer. The water table is the two-dimensional surface between the unsaturated materials above the water table and the saturated materials below. The water level in a well drilled into an unconfined aquifer is the water table. A confined or artesian aquifer is bounded above and below by confining beds that have much lower permeabilities than the aquifer. The water level in a tightly cased well drilled into a confined aquifer will usually be some distance above the top of the aquifer due to the head pressure on the water in the aquifer. If the water level in the well rises above land surface, it is termed a flowing artesian well. The height to which water will rise in the well is represented by the potentiometric surface of the aquifer at that location.

Not all geologic materials are capable of transmitting significant quantities of water. Some geologic formations or materials are *aquicludes*, which are geologic units that are not capable of transmitting significant quantities of water under ordinary gradients. Geologic units or materials that are not permeable enough to be considered aquifers, but are permeable enough to be considered important in terms of regional groundwater flow are called *aquitards*. For example, the Northview Formation in southwest Missouri is considered an aquitard. The Northview contains considerable shale and siltstone, which greatly limits the movement of water through it. However, on a regional scale, the downward movement of water through the Northview

provides considerable recharge to the underlying aquifer. Most geologic units in Missouri are either considered aquifers or aquitards. Only a few geologic units have the hydrologic characteristics of an aquiclude.

There are several other hydrologic terms that are important in describing the movement of groundwater and the hydrogeologic characteristics of aquifers. The *permeability* or *hydraulic conductivity* of an aquifer is defined as the rate of flow of water through a unit cross-section of aquifer under a hydraulic gradient of one. In general, the higher the permeability, the greater the potential volume of groundwater that can move through the unit. A related term, *transmissivity*, is equal to the permeability times the saturated thickness of the aquifer. The term transmissivity is used to describe the water-yielding characteristics of the entire vertical extent of an aquifer, whereas permeability is generally used to describe the water-yielding characteristics of only a particular zone.

The storage characteristics of an aquifer, commonly called the *coefficient of storage*, or simply the *storativity*, is defined as the volume of water the aquifer takes into or releases from storage, per unit surface area, per unit change in water level or head. The units are dimensionless. The storativity of a barrel is one. Each unit volume of the barrel will take into or release an equivalent volume of water. Much of the volume of an aquifer, however, is rock, sand and gravel, or other geologic materials. Only a small fraction of the total volume of rock is available for water storage. In unconfined aquifers, the water is released from storage by the dewatering of openings in the aquifer. The storativity of an unconfined aquifer is generally called its *specific yield*, and it is related to the effective porosity of the rock. The *effective porosity* is the ratio of hydraulically connected void space in the rock to the total volume of rock. If all of the stored water within a given volume of an unconfined aquifer could be released, then

the specific yield would be essentially equal to the effective porosity. However, some of the water in the pores remains behind because of surface tension, so the specific yield is always less than the effective porosity.

The specific yield or storativity of unconfined aquifers is typically between 0.01 and 0.3 (Freeze and Cherry, 1979). The storativity of confined aquifers is much smaller, generally from 5×10^{-3} to 5×10^{-5} . The low values of storativity for artesian or confined aquifers are due to the fact that water released from storage in these aquifers is derived by the compaction of the aquifer and its associated beds and by expansion of the water itself, while the openings in the aquifer remain saturated.

Aquifers are often named after the geologic formation that comprises them. Examples of this include the St. Peter Sandstone, the Missouri River alluvium, and the McNairy Formation. However, unless the specific geologic formation is hydrologically isolated from the units above and below it, it is generally best not to name the aquifer after the geologic unit. In Missouri, several geologic formations commonly comprise a single aquifer. For example, the Ozark aquifer is composed of the geologic units between the base of the Maquoketa Shale (in eastern Missouri) or Chattanooga Shale (in western Missouri) and the base of the Potosi Dolomite. Depending on location, the geologic formations included in the aquifer include the Kimmswick Limestone, Plattin Limestone, Joachim Dolomite, St. Peter Sandstone, Everton Formation, Smithville Formation, "Powell" Dolomite, Cotter Dolomite, Jefferson City Dolomite, Roubidoux Formation, Gasconade Dolomite, Eminence Dolomite, and the Potosi Dolomite. All of these formations are hydrologically connected; there are no major aquitards within the vertical sequence. However, not all of the zones are uniformly permeable. There are specific zones within several of the formations that typically yield most of the water, but all of the units are considered part of the aquifer.

POTABLE GROUNDWATER STORAGE IN MISSOURI

All of the potable groundwater in storage in Missouri originated as, and is recharged by, relatively local precipitation. During years of abundant precipitation, the volume of groundwater in storage generally increases and groundwater levels in shallow aquifers rise. During times of prolonged drought, water levels decline, and the total amount of water in storage decreases.

It is difficult to precisely measure the total volume of groundwater in storage in Missouri. As part of this report, groundwater storage volumes were estimated for the major aquifers in the state that yield potable quality water. Existing geologic and hydrogeologic information was used to calculate groundwater storage by county, aquifer, and groundwater province. The calculations reflect the amount of usable or drainable water that is estimated to be available in the aquifer.

It is estimated that during normal weather cycles, there is approximately 420.7 trillion gallons of potable water stored in the bedrock aquifers of Missouri, and another 25.8 trillion gallons of water stored in the alluvial sand and gravel deposits in the Missouri and Mississippi river floodplains and in the Southeastern Lowlands. Another 44.2 trillion gallons of water is estimated to be stored in the unconsolidated Cretaceous- and Tertiary-age sands and gravels underlying the alluvial deposits in the Bootheel. Glacial drift and other aquifers contain about 9.3 trillion gallons. The sum of the above yield a grand total of about 500 trillion gallons, or almost 1.53 billion acre-feet of fresh groundwater in storage in Missouri aquifers. Table 2 shows storage estimates of potable groundwater for each major aquifer and each county in Missouri.

GENERALIZED MISSOURI GROUNDWATER QUALITY

Water termed "fresh" or "potable" refers to water containing less than 1,000 milligrams per liter (mg/L) of total dissolved solids, and less than 250 mg/L each of sulfate and chloride. These criteria are based, in part, on

secondary water-quality standards used by the Department of Natural Resources for public water supplies. Aquifers that contain potable water in the Ozarks generally contain highly mineralized water in other places. Thus, the total volume of groundwater in storage statewide is somewhat greater than the volume of freshwater available to Missourians.

In many areas of Missouri, the deep aquifer zones contain water that is of poor quality. Total dissolved solids, a parameter which is most often used to denote water quality, can greatly exceed the 500 mg/L public drinking water standard. Figure 5 is a map of Missouri showing a natural feature known as the freshwater-salinewater transition zone. Groundwater contained in deeper aquifer zones south of the transition zone generally contains less than 1,000 mg/L total dissolved solids, and less than 250 mg/L of chloride and sulfate, and is generally potable without treatment. North of the transition zone, groundwater in the same aquifer zones becomes increasingly mineralized and contains excessive total dissolved solids and chloride, and may contain excessive sulfate.

Another factor that appears to be related to the existence of the freshwater-salinewater transition zone, is the presence of hydrogen sulfide gas and higher dissolved radionuclides in groundwater paralleling the transition zone on the freshwater side. Near the transition zone in many areas across Missouri, gross alpha emissions exceed 15 picoCuries per liter, and radium 226 and radium 228 activities exceed 5 picoCuries per liter, the maximum levels allowed for public drinking water. Although it is possible to treat the water to remove the radionuclides, the added expense of removing them from the water and disposing of the slightly radioactive sludge produced by treatment, often causes the owners of small water systems to look for other sources of water.

It is beyond the scope of this report to address water quality in great detail. The reader is referred to *Missouri Water Quality Assessment, Missouri State Water Plan Volume III* (Brookshire, 1997) for a more detailed presentation of groundwater quality.

Table 2. Estimated quantity of potable groundwater in storage in Missouri aquifers (all values are in billion gallons).

County	St. Francois aquifer	Ozark aquifer [south of Missouri River]	Cambrian Ordovician aquifer [north of Missouri River]	Springfield Plateau aquifer [southwest Missouri]	Mississip- -pian- age bedrock aquifer	Pennsyl- vanian- age bedrock aquifer	McNairy aquifer [Southwestern Lowlands]	Wilcox aquifer [Southeastern Lowlands]	Glacial Drift aquifer [north of Missouri River]	Missouri & Mississippi River alluvial aquifers [including Southeast Lowlands]	Other aquifers [including Moberly & Warrensburg sandstones]	County Totals
Adair									58.6			58.6
Andrew									239	29.3		268.3
Atchison									700	310		1010
Audrain			6257		830							7087
Barry	323	5642		306								6271
Barton	220	7982		671		1.3						8874.3
Bates	4.7	133		15.6		87.1						204.4
Benton	350	6842										7192
Bollinger	651	1841								226		2718
Boone			7261		232					54.2		7547.2
Buchanan							1114		104	166		270
Butler	839	3296							22.5	1924		7173
Caldwell												22.5
Callaway			9658		253					98.8		10009.8
Camden	668	5347										6015
Cape Girardeau	837	3128								349		4314
Carroll									199	410		609
Carter	521	1062										1583
Cass						73.2						73.2
Cedar	246	7736	238									8220
Chariton									384	174		558
Christian	437	11449		168								12054
Clark					75.6				58	88.1		221.7
Clay									57.8	91.5		149.3
Clinton									110			110
Cole	409	3986								47.7		4442.7
Cooper	245	5277		56.2						37.7	10.5	5626.4
Crawford	766	5431										6197
Dade	225	8064		435								8724
Dallas	453	6229										6682
Daviess									399			399
DeKalb									345			345

County	St. Francois aquifer	Ozark aquifer [south of Missouri River]	Cambrian Ordovician aquifer [north of Missouri River]	Springfield Plateau aquifer [southwest Missouri]	Mississip- pian- age bedrock aquifer	Pennsylvan- ian- age bedrock aquifer	McNairy aquifer [Southwestern Lowlands]	Wilcox aquifer [Southeastern Lowlands]	Glacial Drift aquifer [north of Missouri River]	Missouri & Mississippi River alluvial aquifers [including Southeastern Lowlands]	Other aquifers [including Moberly & Warrensburg sandstones]	County Totals
Dent	472	5905										6377
Douglas	849	11035										11884
Dunklin	218	436					2282	7552		3027		13515
Franklin	1145	9134								90.3		10369.3
Gasconade	652	5161								18		5831
Gentry									636			636
Greene	494	13256		483								14233
Grundy									453			453
Harrison									951			951
Henry	139	3050		87.1		39.6					8.8	3324.5
Hickory	244	4286		21.5								4551.5
Holt									150	455		605
Howard			119		12.3					99.9		231.2
Howell	773	8217										8990
Iron	190	344										534
Jackson						56.3				93.3	28.2	177.8
Jasper	201	7353		752								8306
Jefferson	854	3735			18.8							4607.8
Johnson	166	3088		85.8		47.7					60.4	3447.9
Knox					110				48.3			158.3
Laclede	801	7967										8768
Lafayette				1.3		63.9				80.4	82.4	228
Lawrence	256	7363		720								8339
Lewis					124				29.1	44		197.1
Lincoln			4250		96.5					124		4470.5
Linn									376			376
Livingston									456			456
McDonald	111	3526		243								3880
Macon									25.2			25.2
Madison	171	62.6										233.6
Maries	551	4955										5506
Marion					75.9					158		233.9

County	St. Francois aquifer	Ozark aquifer [south of Missouri River]	Cambrian Ordovician aquifer [north of Missouri River]	Springfield Plateau aquifer [southwest Missouri]	Mississip- ian- age bedrock aquifer	Pennsylvan- ian- age bedrock aquifer	McNairy aquifer [Southwestern Lowlands]	Wilcox aquifer [Southeastern Lowlands]	Glacial Drift aquifer [north of Missouri River]	Missouri & River alluvial aquifers [including Southeastern Lowlands]	Other aquifers [including Moberly & Warrensburg sandstones]	County Totals
Mercer									601			601
Miller	557	4947										5504
Mississippi							2138	3762		2257		8157
Moniteau	348	4783								18.8		5149.8
Monroe					80.8				13		3.6	97.4
Montgomery			8447		263					51.1		8761.1
Morgan	368	6194										6562
New Madrid												14213
Newton	131	3760		654			1877	8088		4248		4545
Nodaway									1089			1089
Oregon	908	2973										3881
Osage	634	5687								56.8		6377.8
Ozark	534	12196										12730
Pemiscot							2696	11785		3709		18190
Perry	470	1343			60.1					175		2048.1
Pettis	350	7963		101								8414
Phelps	492	6326										6818
Pike			2230		156					77.4		2463.4
Platte									18.7	155		173.7
Polk	398	9439		117								9954
Pulaski	574	2581										3155
Putnam									659			659
Ralls					37							37
Randolph									1.3		5.5	6.8
Ray									32.3	277		309.3
Reynolds	488	1439										1927
Ripley	642	2720								105		3467
St. Charles			5866		511					686		7063
St. Clair	362	7571		189		22.3						8144.3
St. Francois	471	36.5										507.5
Ste. Genevieve	678	469			46.7					12.5		1206.2
St. Louis	189	940			188					142		1459

County	St. Francois aquifer	Ozark aquifer [south of Missouri River]	Cambrian Ordovician aquifer [north of Missouri River]	Springfield Plateau aquifer [southwest Missouri]	Mississip- pian- age bedrock aquifer	Pennsylvan- ian- age bedrock aquifer	McNairy aquifer [Southwestern Lowlands]	Wilcox aquifer [Southeastern Lowlands]	Glacial Drift aquifer [north of Missouri River]	Missouri & Mississippi River alluvial aquifers [including Southeastern Lowlands]	Other aquifers [including Moberly & Warrensburg sandstones]	County Totals
Saline				5.2		18.2				180	171	374.4
Schuyler									55.4			55.4
Scotland					29.5				74.1			103.6
Scott	559	1865					682	104		2042		5252
Shannon	1037	5193										6230
Shelby					85.7				29.5			115.2
Stoddard	1220	2982					1389	684		3266		9541
Stone	248	8697		54.7								8999.7
Sullivan									468			468
Taney	380	9510										9890
Texas	1107	6768										7875
Vernon	96	4786		320		44						5246
Warren			6710		47.2					109		6866.2
Washington	665	2033										2698
Wayne	594	2857								49.1		3500.1
Webster	620	11614		19.9								12253.9
Worth									348			348
Wright	771	8890										9601
Aquifer Totals	31312.7	328881.1	50798	5744.3	3333.1	453.6	12178	31975	9190.8	25812.9	370.4	500049.9



Figure 5. Freshwater-salinewater transition zone.

THE HYDROLOGIC CYCLE

All of Missouri's water resources, surface water and groundwater, originate as precipitation, most in the form of rainfall. Considerable surface water enters Missouri from neighboring states, but most of Missouri's groundwater travels much shorter distances. Rainfall amounts vary significantly from northwest to southeast across the state (figure 6). During an average year, extreme northwestern Missouri receives less than 35 inches of precipitation while the southeastern corner of the state receives about 48 inches.

PRECIPITATION, EVAPOTRANSPIRATION, AND RUNOFF

Although yearly precipitation in Missouri typically ranges from 35 inches to 48 inches, only a fraction of this becomes either surface-water runoff or groundwater recharge (figure 7). Most of the precipitation is lost back into the atmosphere through evaporation, or is used by plants through transpiration (figure 8). Combined, these losses are called *evapotranspiration*, and on the average they range from about 26 inches in northwestern Missouri to about 30 inches in southeastern Missouri. Generally, evapotranspiration rates are highest during hot summer months and least during winter and spring. However, before evapotranspiration can occur the soil must contain moisture. During droughts, evapotranspiration may actually be low because of lack of soil moisture.

Like precipitation and evapotranspiration, runoff in Missouri increases from about

5 inches per year in northwestern Missouri to about 20 inches per year in southeastern Missouri. These values are based on discharge measurements at long-term gaging stations on Missouri rivers and streams. The discharge measurements, though, include groundwater inflow into the streams as well as direct surface-water runoff into them. In northern and western Missouri where streams flow through low-permeability glacial drift and Pennsylvanian-age bedrock, little groundwater enters the streams. However, in the Ozark region where rivers and streams cut through thick limestone and dolomite formations there are many springs that feed the rivers and streams. Much of the surface water in Ozark rivers and streams is provided by groundwater that flows into the streams through springs, seeps, and general groundwater inflow.

TYPES OF GROUNDWATER RECHARGE

DIFFUSE GROUNDWATER RECHARGE

Groundwater recharge can be broadly categorized into two types—*diffuse recharge* and *discrete recharge*. Diffuse recharge is the relatively slow infiltration of water from the Earth's surface into the groundwater system. Diffuse recharge is generally slow, and consists largely of water moving downward through soil materials and weathered rock, through permeable sand and gravel in unconsolidated sediments or small cracks and crevices in bedrock. Diffuse recharge can occur almost anywhere that the soils or surficial

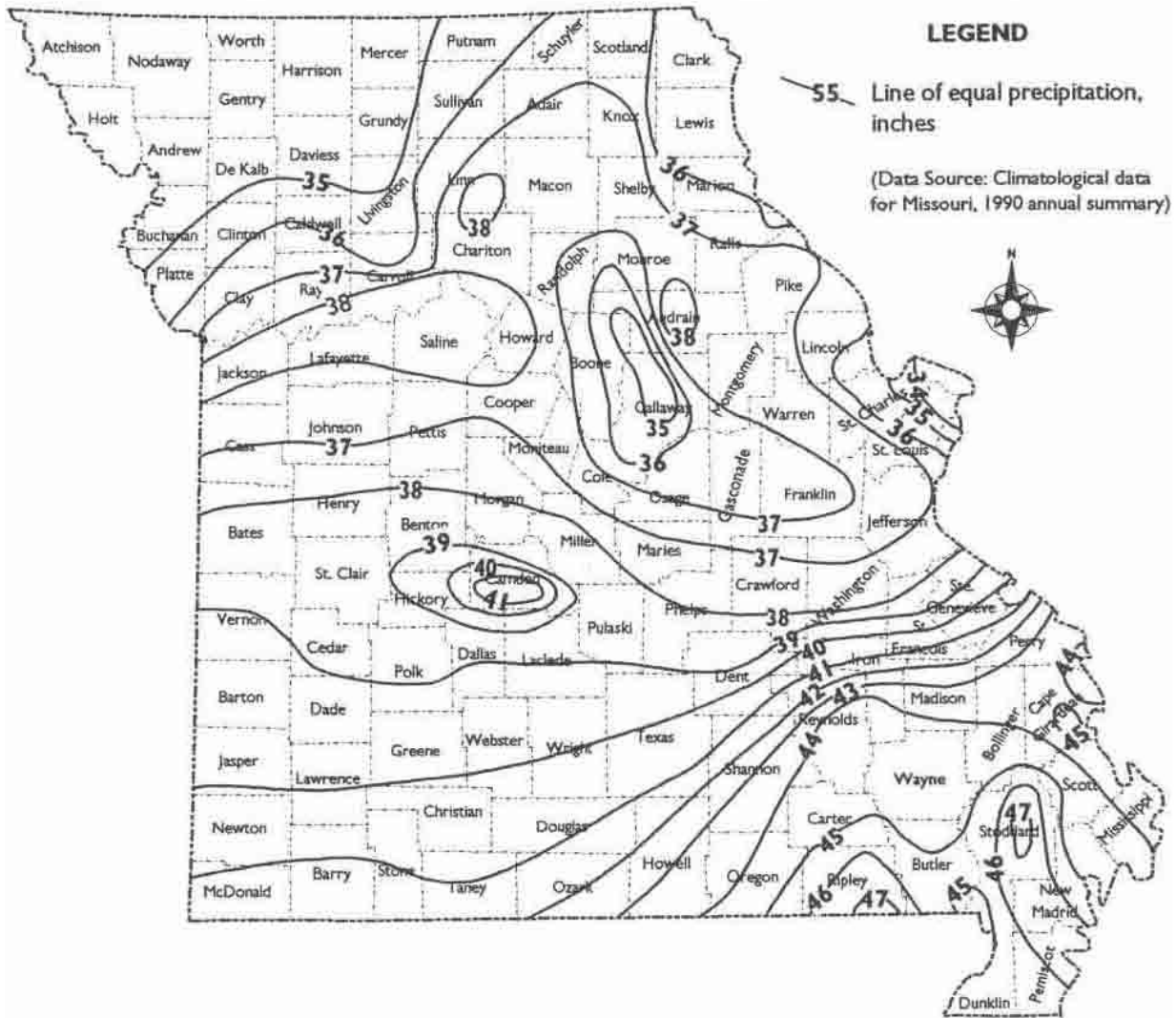


Figure 6. Long-term average annual precipitation in Missouri.

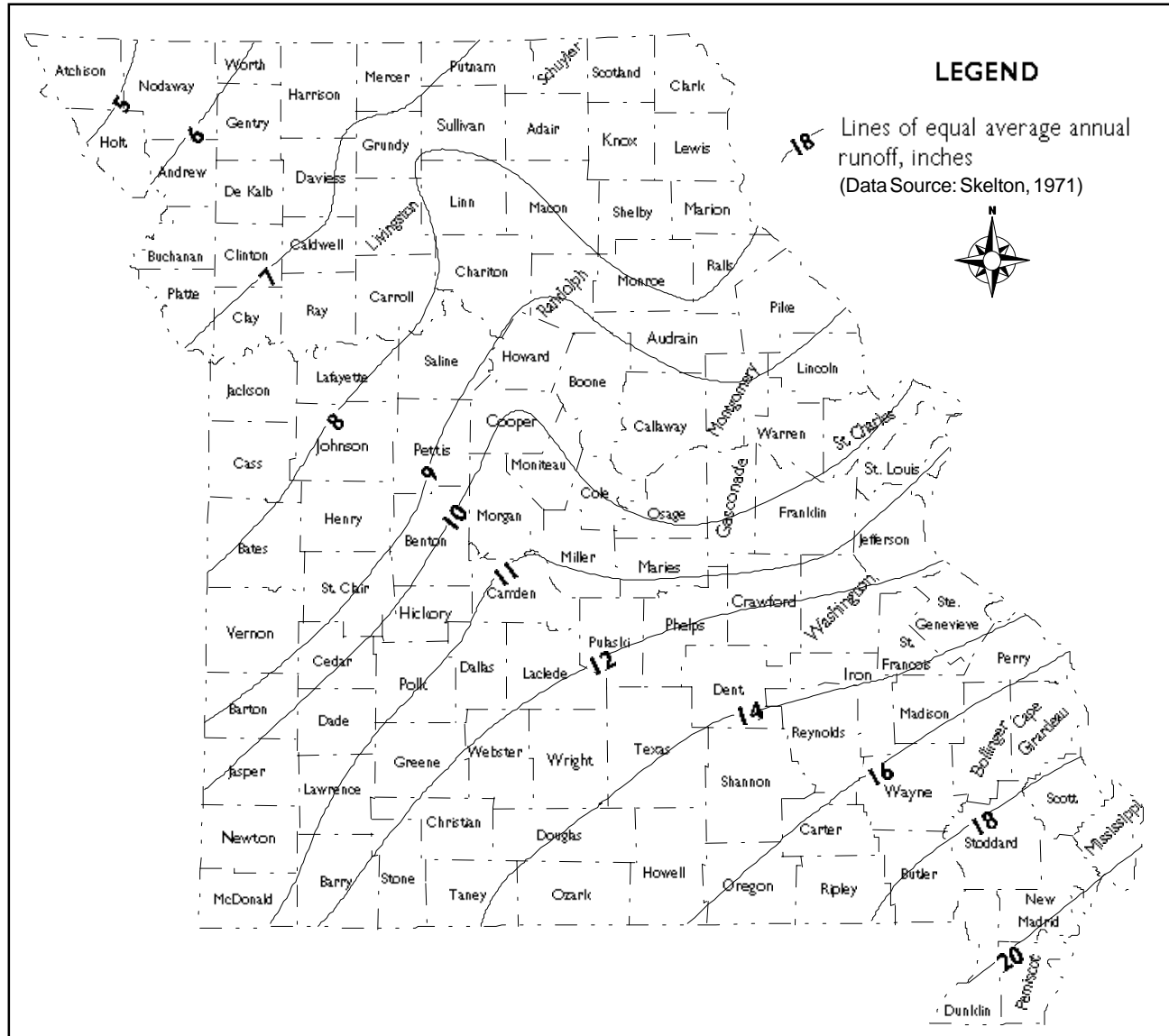


Figure 7. Average annual runoff in Missouri.

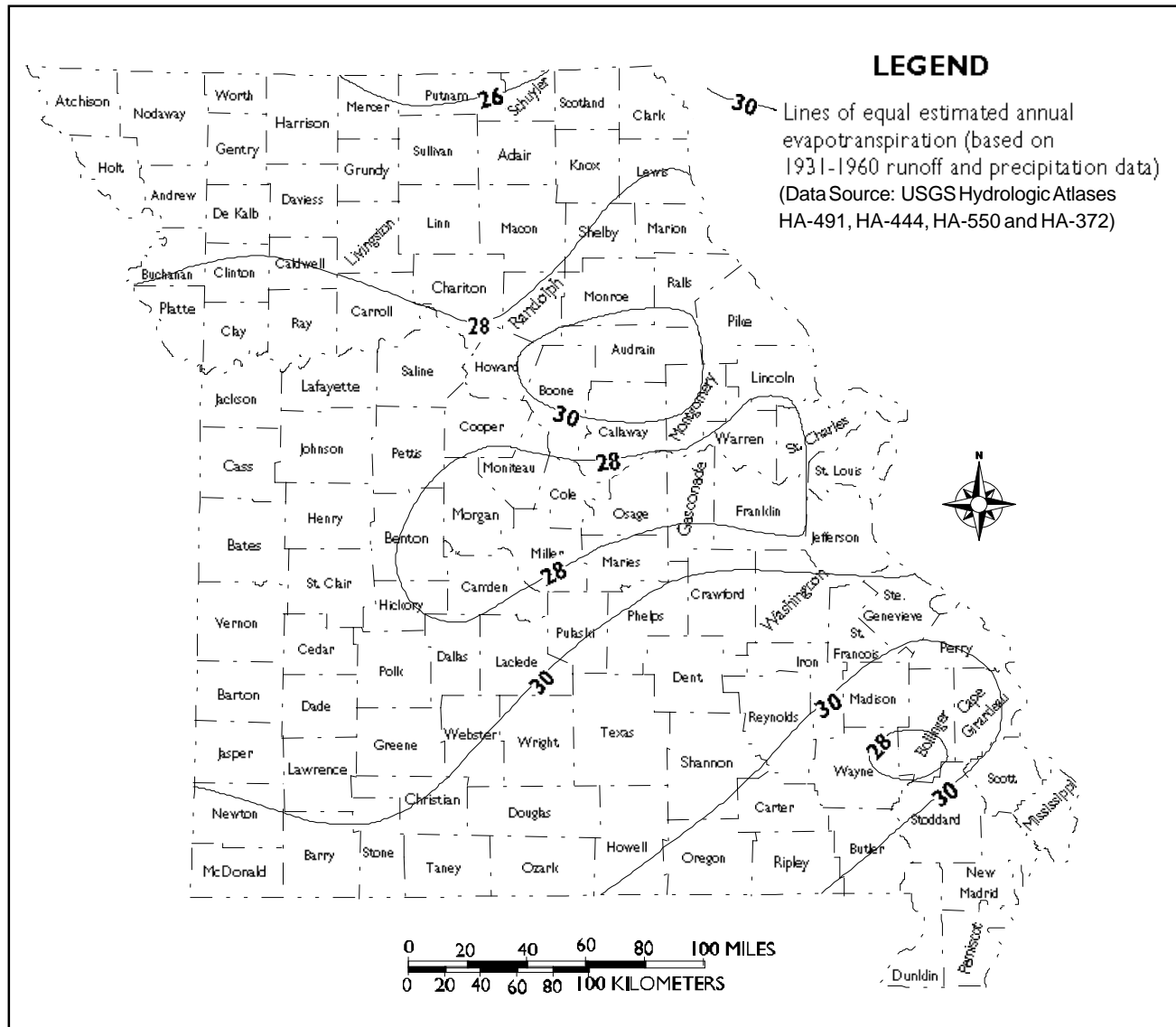


Figure 8. Estimated annual evapotranspiration losses in Missouri.

materials are permeable enough to allow water movement. This type of recharge occurs in the glacial drift areas of northern Missouri as well as the alluvial plain of the Bootheel and nearly all points in between. The more permeable the surficial materials and shallow bedrock are, the greater the recharge.

In terms of diffuse groundwater recharge, the amount of precipitation an area receives may not be as important as the temporal and spacial distribution of precipitation. For example, an intense rainstorm occurring for a brief time during the summer generally provides less groundwater recharge than a gentle, prolonged rain lasting an extended period in the spring or fall of the year; even though the rainfall amounts are the same in both events. Direct runoff after a brief, hard rain during the summer months is much greater and more rapid than runoff after a prolonged, gentle rain during the spring or fall. The slope of the terrain, the type of soil, and the amount of vegetation are also important factors to consider when determining the efficiency of a region to have significant diffuse recharge to underlying aquifers.

Diffuse recharge typically provides a relatively small volume of recharge per unit area, but since it occurs over broad regions it ultimately supplies very large quantities of groundwater recharge. There are large regions where almost no groundwater recharge occurs, and much smaller areas where rather large amounts of recharge take place. Estimates as to how much of the total water available from rainfall actually becomes diffuse recharge range from a low of less than one inch per year in low-permeability glacial drift and Pennsylvanian shales to more than 8 inches in sandy alluvium in the Southeastern Lowlands. Although these values seem low, if the total area of the state is considered, the resulting volume of diffuse groundwater recharge is large. Assuming a statewide average diffuse recharge of 4 inches, diffuse recharge supplies about 4.85 trillion gallons of recharge per year, enough water to supply each of Missouri's 5.2 million residents 150 gallons of water per day for over 17 years.

DISCRETE GROUNDWATER RECHARGE

Another more spectacular type of recharge occurs in many areas of the state, especially in southern Missouri. This type of recharge, called *discrete recharge*, occurs in Missouri in areas where the dissolution of limestone and dolomite bedrock has occurred. Discrete recharge is the localized, concentrated movement of water from land surface into the subsurface. It typically occurs where karst groundwater recharge features have developed. *Karst* is a term used to denote areas where the topography is mostly formed by the dissolving of soluble rock such as limestone and dolomite. Rainwater passing through the atmosphere absorbs carbon dioxide and becomes slightly acidic. Acidity increases as the water moves through the soil materials absorbing more carbon dioxide and organic acids. The water dissolves the limestone and dolomite as it moves through fractures, bedding planes, and pores in the carbonate bedrock; each drop of water removing a minute quantity of rock. The more rainfall that can be recharged, the larger the openings grow, and the deeper the circulation. Over time, karst features evolve such as sinkholes, losing streams, springs and caves.

Sinkholes are topographic depressions in the Earth's surface caused by the subsurface removal of soil and rock. They result where soluble bedrock is dissolved by slightly acidic groundwater and the dissolved materials, along with some of the remaining insoluble parts of the rock, are transported underground through solution-enlarged openings in the bedrock. A void is formed as the bedrock dissolves, and over time the opening enlarges to the point that the roof is unable to sustain its own weight and a collapse occurs. If the newly formed sinkhole is developed mostly in residual materials, it will likely have nearly vertical or overhung sides, and little or no bedrock exposed in the walls. Over time, erosion will erode material around the rim, yielding the more typical bowl-shaped depression. Some sinkhole collapses occur in bedrock, typically where the roof of an underlying cave or void space is too weak for self support (figure 9).

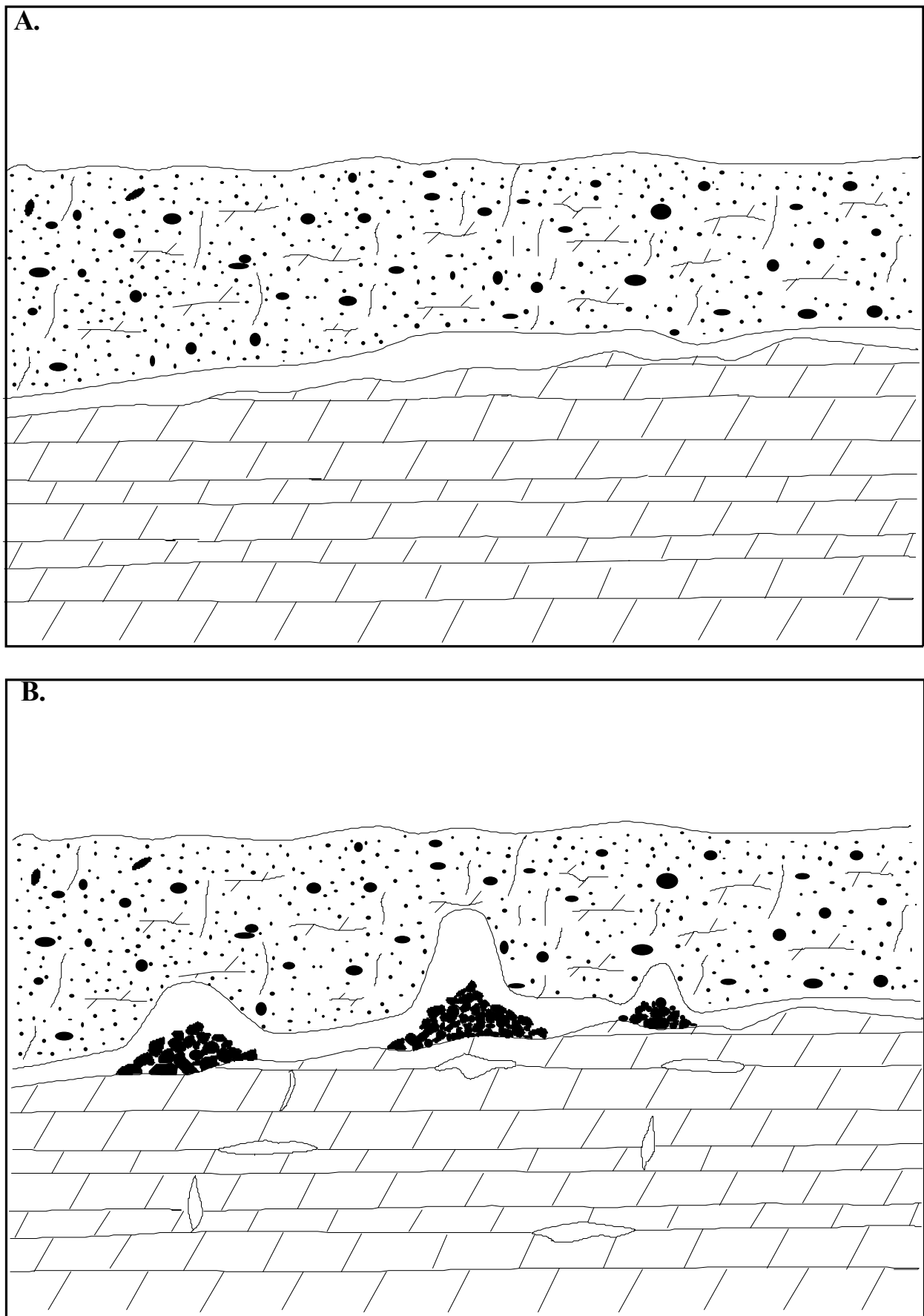
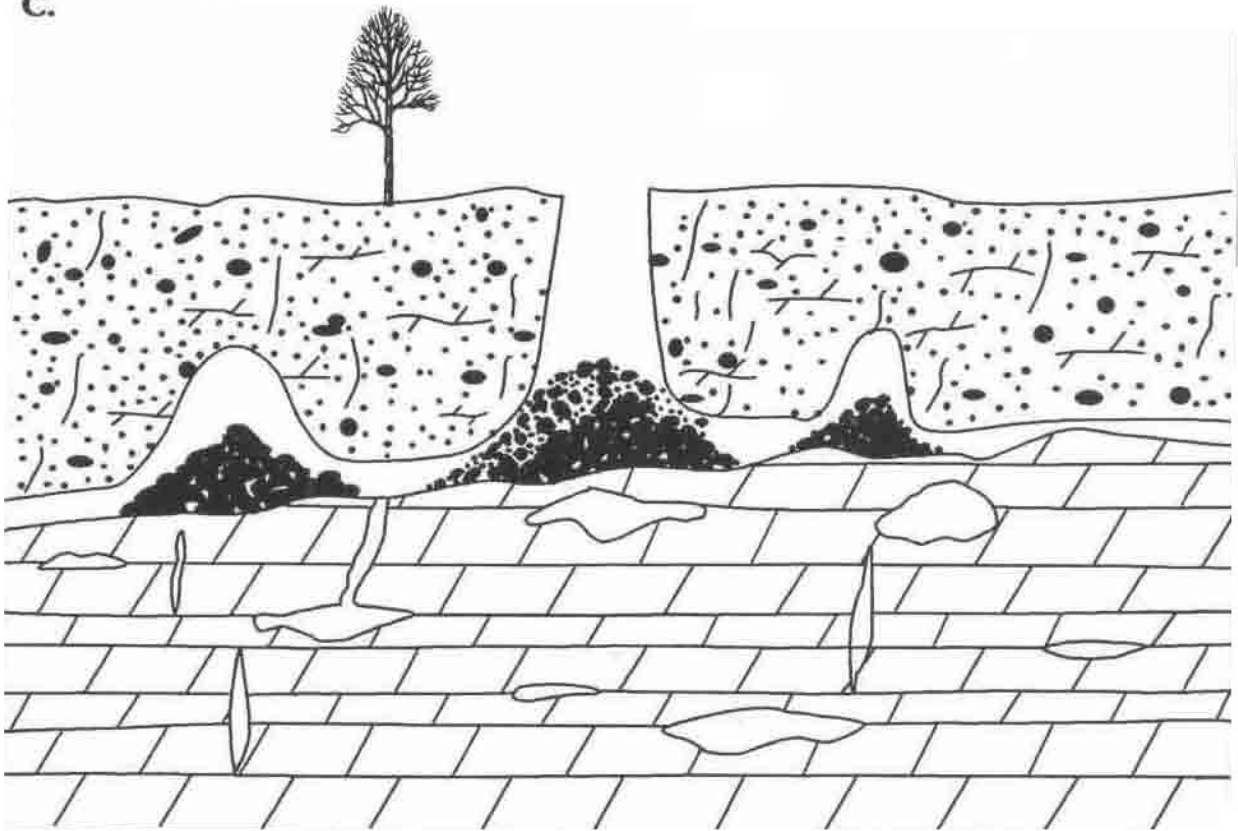
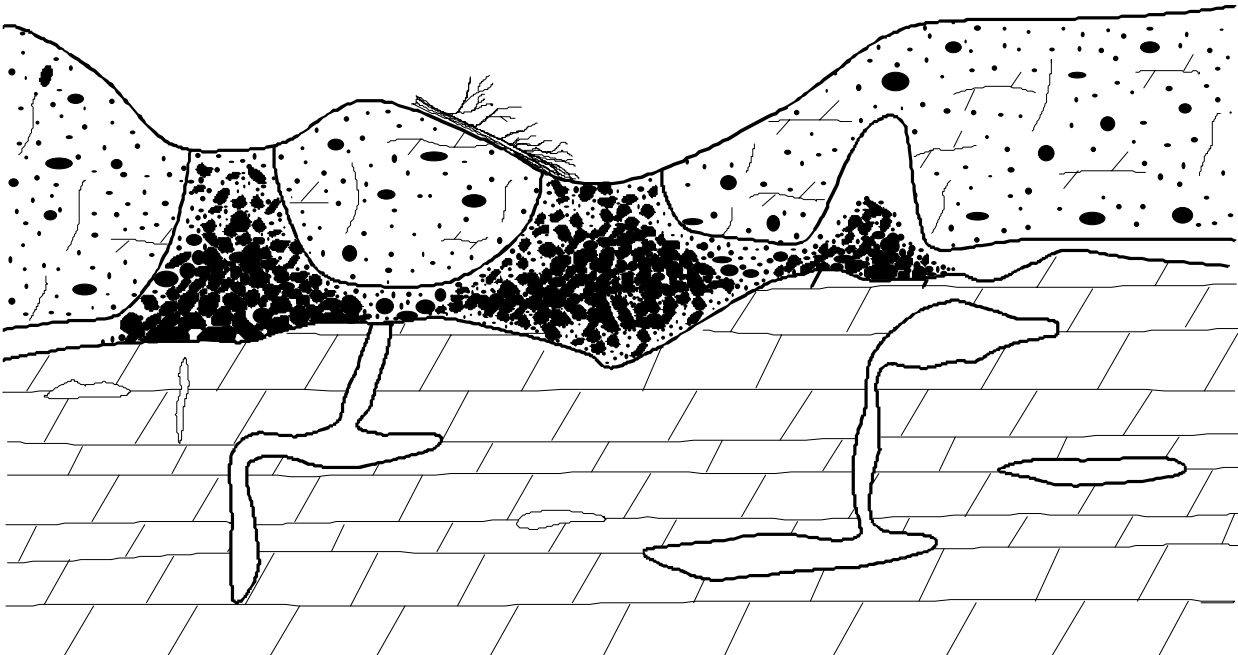


Figure 9. Stages of sinkhole development in residual materials.

C.



D.



Sinkholes are discrete groundwater recharge features. They act as natural funnels, collecting and channeling underground the runoff that occurs within their catchment areas. Most sinkholes do not have large openings in their bases, but some are cave entrances. Even if large openings are lacking, the bottoms of most sinkholes are permeable enough to allow significant groundwater recharge. Unless a sinkhole fills completely and overtops, there is no surface-water outflow. Thus, all of the water entering the sinkhole from precipitation that is not evaporated or transpired is available for groundwater recharge.

Sinkholes range in size from depressions a few feet across and a few feet deep, to more than a mile in diameter and several hundred feet deep. Their drainage areas likewise vary greatly, from less than an acre to several square miles.

Streams that maintain flow essentially year-round and have flows that are well-sustained or increase in a downstream direction are called *gaining streams*. The water table along gaining streams is generally at or above stream level, and groundwater generally moves toward and into the stream. Losing streams are just the opposite. *Losing streams* are those that lose a significant part of their flow into the groundwater system. Like sinkholes, they are discrete recharge features that allow surface water to rapidly enter the subsurface. The water table along losing streams is below stream elevation. The water is generally lost into the subsurface through solution-enlarged openings beneath the streambed, openings that may be covered by gravel, sand, or other alluvial materials. Figure 10 is a photograph of Goodwin Hollow north of Lebanon in Laclede County. Although the stream drains nearly 70 square miles above this point, it seldom carries flow except after heavy or prolonged rainfall.

Unlike sinkholes, losing streams do not necessarily direct all of the water flowing in them into the subsurface. Also, a given stream can contain both gaining and losing reaches. Some streams have perennial or year-around flow in the upstream reaches while the valley

farther downstream contains a losing reach and is typically dry. Others streams may lose flow in the upstream reaches but are perennial in the downstream reaches. A few losing streams have well-sustained flows throughout the losing reaches, but lose only part of the water. Some are essentially dry all of the time from headwaters to mouth. Few if any losing streams channel all of the runoff underground. Most losing streams will carry some flow after heavy, prolonged precipitation. However, even after very heavy rainfall, the flows of most losing streams decrease rapidly to zero within a few days after the precipitation ends.

Hydrologically, both losing streams and sinkholes can be thought of as the upstream ends or entry points of karst drainage systems. Springs are the groundwater outlets at the downstream end where the water lost underground through sinkholes and losing streams, as well as water provided by diffuse recharge, is returned to the surface. Connecting them are groundwater conduits, or cave-like openings, that can rapidly transport water through the karst drainage system. In the case of large springs, the conduits may be many feet in diameter and are essentially water-filled caves. Conduits feeding lesser springs may be little more than solution-enlarged fractures and bedding plane openings only a few inches across.

The volume of discrete recharge that occurs in Missouri each year is enormous. There are thousands of sinkholes and hundreds of miles of losing streams in the state. Most of these features are south of the Missouri River in the Ozark region, but a few significant karst areas extend north of the river, mostly in Boone County and counties bordering the Mississippi River downstream near Palmyra. Although the volume of discrete recharge is enormous, most of this water remains underground for only a short period of time, only a few days or weeks. Recharge through sinkholes and losing streams is rapid, and the groundwater conduits quickly transport most of the water to the receiving springs. Water tracing studies have shown that groundwater can move more than a mile per day through

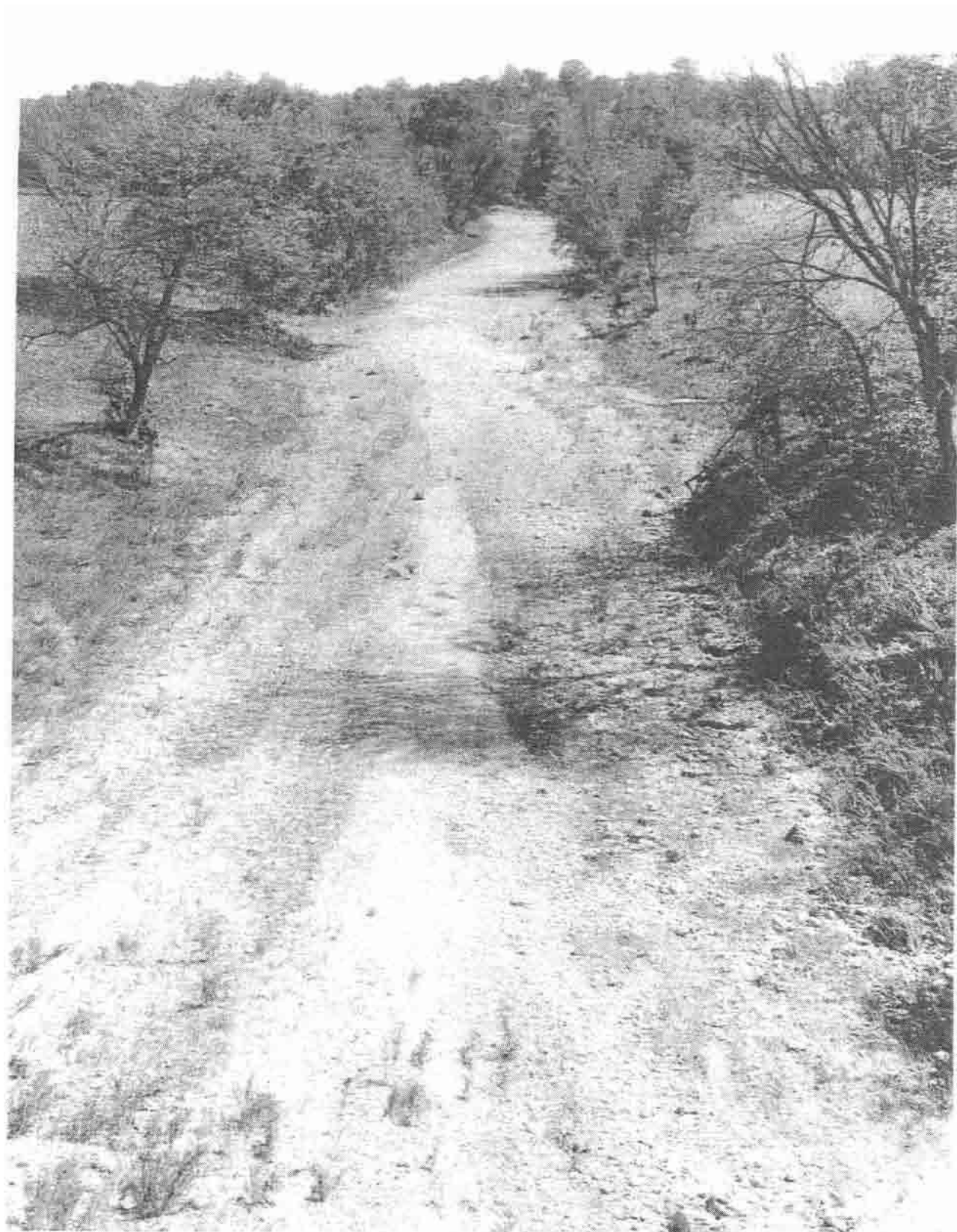


Figure 10. Goodwin Hollow is a major losing stream in Laclede County. Above this point, Goodwin Hollow drains more than 70 square miles but is typically dry due to water loss into the subsurface. Photo by Jim Vandike.

the karst groundwater systems. Water moving through karst drainage systems can be traced using several techniques, but generally fluorescent dyes are employed. To conduct a water trace, a fluorescent dye or other suitable substance is introduced into water where it disappears into the subsurface through the base of a sinkhole or in a losing stream. Springs and gaining streams in the area are monitored to determine where the tracing agent resurfaces. Water tracing allows a physical connection to be established between recharge and discharge points. It does not, however, show the actual path that the water followed during its journey.

Although most of this water does not remain underground very long, its importance should not be underestimated. At one time, springs supplied the drinking water for many

people, and provided power to early industries such as gristmills, sawmills, electrical generators, and iron works. Today, few industries rely on springs for power, and most rural residents use wells for their source of drinking water or obtain water from rural water districts. A handful of towns still use springs to supply part of their water, but most use wells, reservoirs, or rivers. The value of springs today lies more in recreation and wildlife habitat. Springs are used extensively to supply fish hatcheries in Missouri, and provide habitat for trout. Without springs, the clear, cool Ozark streams that canoeists are so fond of would not be floatable most of the time. During dry weather, nearly all of the water in Ozark rivers and streams is from groundwater supplied through seeps and springs.

RESOURCE DESCRIPTIONS FOR MISSOURI GROUNDWATER PROVINCES

For the purpose of this resource evaluation, Missouri has been divided into seven groundwater provinces whose boundaries are similar to those of the physiographic provinces described early in this report. Among the factors considered in delineating the provinces were aquifer boundaries, aquifer types, groundwater quality, distinct geologic features and aquifer vulnerability to contamination. The geology and hydrogeologic characteristics of specific formations will be discussed, as well as the hydrogeologic characteristics of regional aquifers. In

addition, groundwater storage estimates are presented for the various aquifers in each groundwater province.

The seven groundwater provinces used in this report are the St. Francois Mountains, the Salem Plateau, the Springfield Plateau, the Southeastern Lowlands, Northeastern Missouri, Northwestern Missouri, and West-central Missouri. The alluvial valleys of the Mississippi and the Missouri rivers are discussed as subprovinces, but are considered to be within the other groundwater provinces (figure 11).

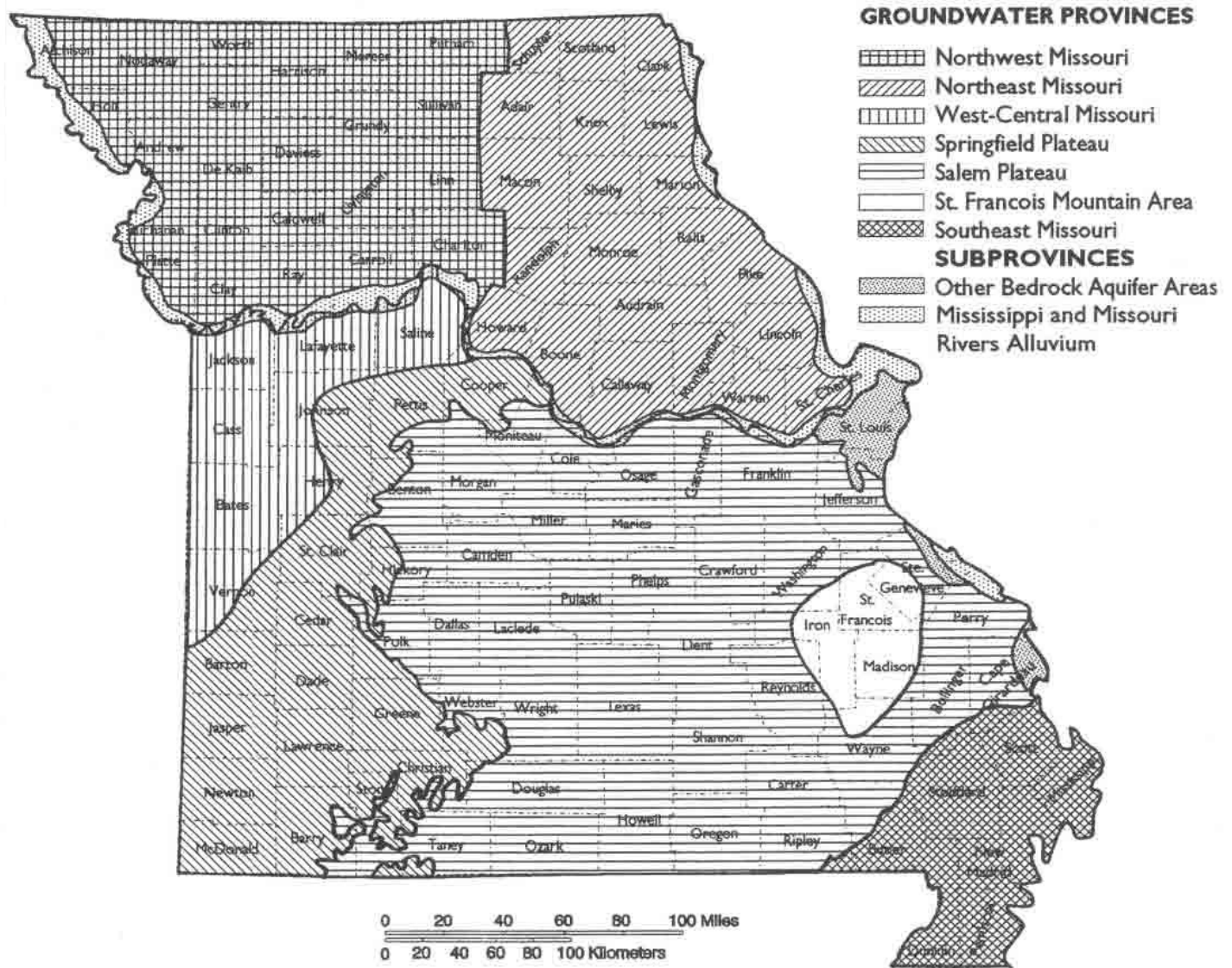


Figure 11. Groundwater provinces and subprovinces of Missouri.

THE ST. FRANCOIS MOUNTAINS GROUNDWATER PROVINCE

INTRODUCTION

The Ozark Plateau physiographic province covers most of southern Missouri and contains many of the states most prolific bed-rock aquifers. The region can be subdivided into the St. Francois Mountains, the Salem Plateau and the Springfield Plateau, and will be discussed in that order.

The St. Francois Mountains province is structurally and topographically the highest point in Missouri. Rock outcropping in this area ranges from Precambrian igneous rock to Upper Cambrian-age clastic and carbonate units. The Precambrian igneous rock forms the core of the St. Francois Mountains, and the younger sedimentary units dip or tilt away from the core, becoming progressively deeper as distance from the St. Francois Mountains increases. Sedimentary rock formations cropping out in the St. Francois Mountains are a thousand feet or more deep in northern and western parts of the state. The province occupies an area of about 1,300 square miles, and covers all or parts of seven counties, including Iron, Madison, Reynolds, St. Francois, Ste. Genevieve, Wayne and Washington.

GEOLOGY

Deposition of sedimentary rock in the Ozarks began when seas transgressed over the Ozark region in the latter part of the Cambrian Period. Deposition was mostly a continuous process through the remainder of the Cambrian and the Lower Ordovician periods, with no major periods of emergence or interruption in deposition between individual

rock units. Where one formation overlies another with no apparent pause in deposition, the units are said to be *conformable* with one another. In some instances, however, there are gaps in the geologic record that resulted from either nondeposition or deposition followed by erosion. These gaps or hiatuses in the geologic sequence are called *unconformities*. There are several major unconformities throughout the geologic record in Missouri. Such an unconformity exists between the Precambrian crystalline rocks and the overlying Cambrian strata. The time gap between the two is about a billion years.

The St. Francois Mountains form the core of the Ozark uplift, which was geologically active throughout most of late Cambrian time. When the entire midcontinent was covered by vast inland seas the Precambrian igneous and metamorphic rocks at the core of the uplift were emergent. Essentially, this emergent cluster of Precambrian rocks resembled islands of igneous rock rising above the level of the shallow seas that inundated this area. Over time, erosion attacked the emergent igneous and metamorphic rocks and generated large volumes of sand and igneous rock fragments. These clastic sediments were transported into the shallow seas. Coarser sediments were deposited closest to shore, particularly in the intervening basins between emergent igneous knobs. Finer sediments were carried farther from the source area. Limestone was deposited in deeper water away from the Precambrian highland as it was being destroyed by erosion. Eventually, the core was

eroded to a point that the seas covered the knobs, and younger sediments were deposited upon them. Later uplift of the Ozark Dome and subsequent erosion reexposed some of the igneous knobs. The uplift and subsequent erosion cycle also left the sediments around the perimeter of the knobs, dipping away from the uplift. Figure 12 is an idealized illustration of the geology and geomorphology of the Precambrian crystalline rock-Cambrian sedimentary rock relationship.

Table 3 is a detailed stratigraphic section of the rocks in the St. Francois Mountains groundwater province.

PRECAMBRIAN SYSTEM

The oldest rocks exposed in Missouri crop out in the St. Francois Mountains and are igneous in origin. Most of the exposed Precambrian igneous rocks consist either of rhyolites or granites (figure 13). The two are chemically similar, but the rhyolites are extrusive; they are chiefly volcanic ash-flow tuffs that formed when magma was extruded onto the Earth's surface and quickly cooled. The rapid cooling of the rock did not allow formation of mineral crystals. The granites, on the other hand, are intrusive igneous rock. They are much more coarsely-crystalline because they formed where magma was allowed

to cool more slowly. Mafic igneous rocks, mostly diabase and basalt, intrude both the rhyolites and granites and occur as vertical dikes and horizontal sills.

Although they crop out mostly in the St. Francois Mountains in Missouri, Precambrian rock underlies all of Missouri at depth.

CAMBRIAN SYSTEM

Lamotte Sandstone

The Upper Cambrian Lamotte Sandstone is the oldest Paleozoic unit in the St. Francois Mountains. It crops out mostly on the northeastern side of the St. Francois Mountains, and forms the surface bedrock unit over an area of about 190 square miles. The unit rests unconformably on Precambrian igneous rock. The Lamotte is predominantly a quartzose sandstone that locally, particularly near its base, grades into arkosic sandstone or conglomerate. The sandstone itself can range in color from almost white through shades of gray, and in some places can be dark brown and even red. Locally, sandy dolomite and also reddish shale is present in the upper part at some locations. Arkosic sands are prevalent throughout the formation. Pebble conglomerates are locally distributed and not unusual in the lower one third of the unit. Weathered zones, which may indicate several phases of

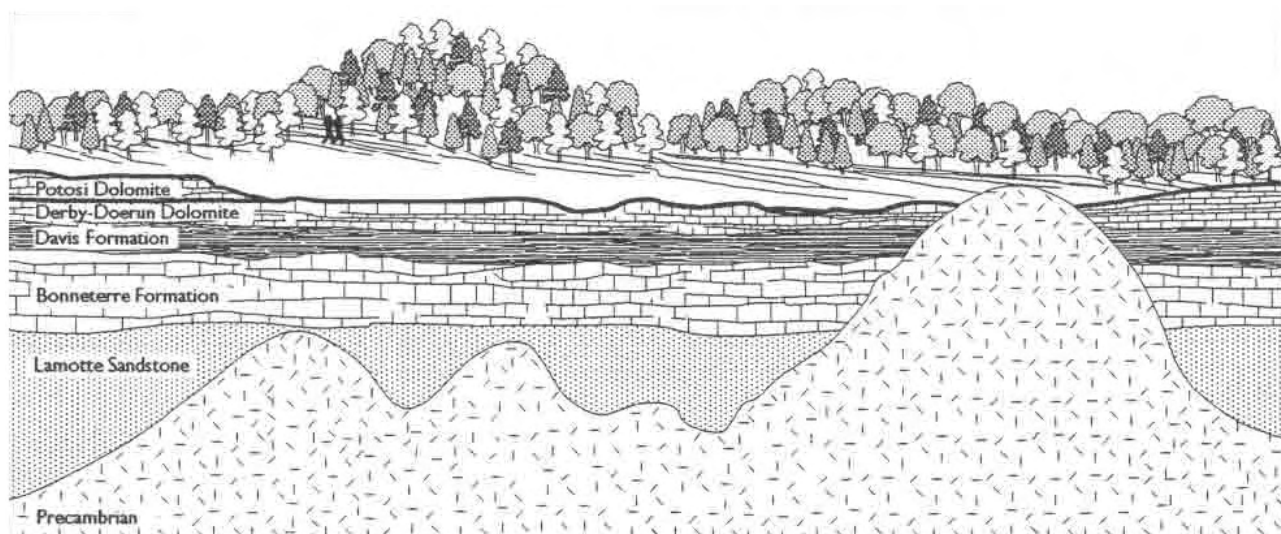


Figure 12. Idealized relationship between Precambrian igneous rocks and younger sedimentary rocks in the St. Francois Mountains area.

System	Series	Aquifer	Group or Formation	Thickness (in Feet)	Lithology	Hydrology
Cambrian	Croixian	Ozark Aquifer	Eminence Dolomite	0-150 Average 75	Similar to Ozark province. Deep fracturing has allowed extensive weathering of this unit.	Does not yield significant amounts of water in this province
			Potosi Dolomite	260-470 May be absent locally	Similar to Ozark province. Highly fractured and locally deeply weathered.	Small to moderate yield, 10-15 gpm
		St. Francois Confining Unit	Derby-Doerun Dolomite	45-160 Average 120	Similar to Ozark province. Chert-free dolomite with glauconite in lower part. May locally have gray-brown shale throughout.	Has poor water-yielding characteristics
			Davis Formation	75-200 Average 125 May be absent locally	Dolomitic shale, sandy dolomite, sandstone or limestone. Unit is highly variable.	Not an aquifer
		St. Francois Aquifer	Bonneterre Formation	175-535 Average 400 May be absent locally	Similar to Ozark province. Lower sandy phase may be replaced by interbedded dolomite and clastics. May rest on Precambrian where Lamotte is missing.	Yields small amounts of water to wells (3-20 gpm)
			Lamotte Sandstone	0-440	Similar to Ozark province. More arkosic near base with pebble conglomerates in lower third, also igneous fragments.	Yields 60-470 gpm Average yield 150 gpm
Precambrian		Basement Confining Unit	Igneous and Metamorphic Rocks			Not an aquifer

Table 3. Stratigraphic section of the St. Francois Mountains groundwater province.

deposition or changes in sea level during deposition, are not unusual to find. Locally, there are zones in the Lamotte that contain considerable igneous material. The material in these zones appears to be derived from nearby igneous intrusives into the Lamotte or from periods of more intense erosion and transport of material from adjacent Precambrian knobs.

In the interior of the St. Francois Mountains province (mostly in Iron, St. Francois, and Madison counties), the Lamotte occurs only sporadically, and the overlying Bonneterre Formation rests directly on Precambrian rock throughout much of the area (figure 14). Locally, the Bonneterre Formation

is also absent, and the Precambrian is overlain by the Davis Formation.

The Lamotte Sandstone in this province ranges in thickness from zero to as much as 440 ft. Where it is thickest, the unit is composed of relatively clean sandstone, with very few zones of arkosic material, igneous fragment zones, shale, or dolomitic intervals. In areas where the unit thins, the Lamotte contains numerous intervals of these more exotic lithologies.

Yields of wells completed in relatively thick sections of Lamotte Sandstone in this province range from about 60 gpm to 470 gpm, and average about 150 gpm. Specific capacities are typically low, ranging between 0.5 and 1.5 gpm/ft.



Figure 13. The contact between the Precambrian-age Taum Sauk Rhyolite and Upper Cambrian-age Davis and Derby-Doerun shaley dolomite in the St. Francois Mountains area near the Taum Sauk hydroelectric power plant. Photo by Jim Vandike.

The natural quality of water from the Lamotte is quite good. Typically, its total dissolved solids content is lower than water produced from the carbonate aquifers of the Salem Plateau groundwater province. Total dissolved solids range between 106 mg/L and 540 mg/L. Locally, there are areas of elevated radionuclides in this province, even though it is some distance from the freshwater-salinewater transition zone. Elevated radionuclides in the Lamotte Sandstone, including gross alpha, radium-226, and radium-228, are thought to be due to the natural radioactivity of certain igneous rock bodies whose weathered sediments form the arkosic parts of the Lamotte. The elevated radionuclides in water from the Lamotte occur locally throughout the eastern part of the province, particularly near the city of Fredericktown in Madison County.

Bonneterre and Davis Formations and Derby-Doerun Dolomite

In areas where the Lamotte Sandstone is present, the Bonneterre Formation conformably overlies it. However, the Lamotte is absent throughout a large part of the province and where it is, the Bonneterre rests unconformably on the Precambrian surface. It is in this area where the Lamotte “pinches” or thins to a featheredge against the Precambrian knobs, that mineral exploration companies find the predominance of lead mineralization, and where most of the major ore deposits have been found in Missouri.

The Bonneterre is a fine- to medium-crystalline dolomite and locally can be a limestone. In places it contains thin shale layers or partings, but typically is a carbonate unit with a low clastic content. In the Salem Plateau, and

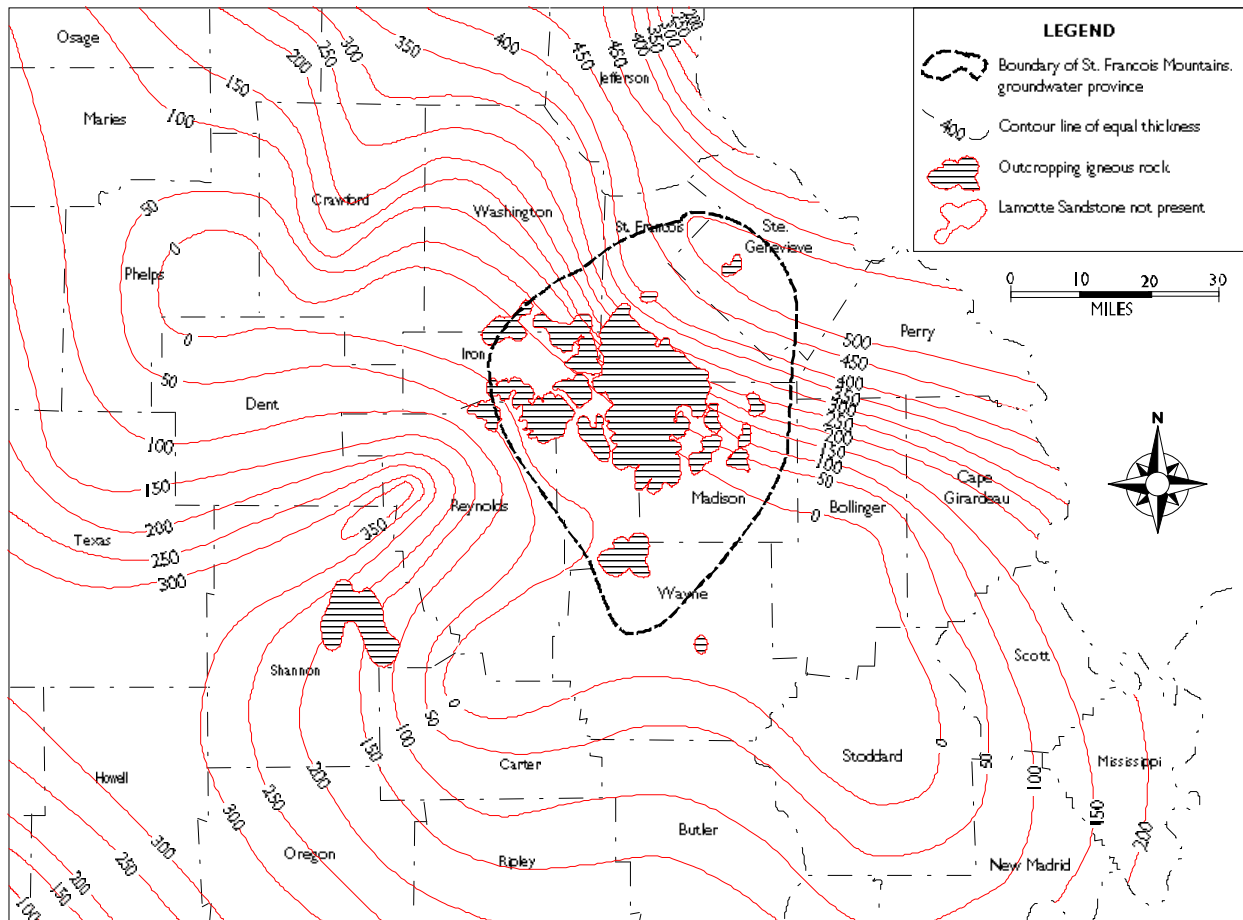


Figure 14. Isopach map of the Lamotte Sandstone in and around the St. Francois Mountains area (Bohm, 1981).

along the margins of the St. Francois Mountains, the lower Bonneterre appears to have a gradational contact with the Lamotte, containing alternating beds of dolomite and sandy dolomite. Sand content increases towards the base of the Bonneterre. Where the Lamotte is absent, however, this sandy transition is replaced by a zone of clastics and interbedded dolomite. The clastics were obviously derived from the weathering of the underlying Precambrian rocks.

The Bonneterre Formation ranges in thickness in this province from zero to 535 ft, and averages approximately 400 ft. There are areas around the margins of the individual basins within this province where the Bonneterre is extremely thin or missing. Here, the overlying Davis Formation may rest unconformably on Precambrian rocks. There is no obvious correlation between thickness

of the Bonneterre and the presence or absence of the underlying Lamotte Sandstone. Where the underlying Lamotte is present, the lower 30 to 60 ft of the Bonneterre locally contains a depositionally restricted facies. This facies, known historically and informally as the Taum Sauk Limestone, is very finely-crystalline, chert-free, and red- to dark-reddish brown. The unit has been quarried in the past to provide terrazzo stone.

Yields of wells completed in the Bonneterre in the St. Francois Mountains province, are relatively small, ranging from 3 to 20 gpm. The relatively chert-free limestone and dolomite has a high enough silt and clay residue that when fractured, any secondary permeability which might be produced by fracturing is usually plugged before it can be solutionally enlarged.

The Davis Formation in the St. Francois Mountains province shows considerable vari-

ability in lithology from one locality to another, even within short distances. Locally, it can be dolomitic shale, sandy dolomite or nearly pure dolomite that is interbedded with shale, sandstone or limestone, all within an area of a few square miles. Such variation typically indicates multiple, rather restricted, depositional environments. The thickness of the Davis in this province averages about 125 ft, and ranges from 75 to 200 ft. There are areas around the margins of the individual basins within the province where the Davis, Bonneterre, and Lamotte are missing, and the younger Derby-Doerun Dolomite rests unconformably on the Precambrian basement rocks.

There are no data indicating that any well has ever produced appreciable groundwater from the Davis in this province. Where the unit is mostly shale, vertical and horizontal hydraulic conductivities are very low, but even where the unit is composed of a mix of dolomite and sandstone its hydraulic conductivity is still very low.

The Derby-Doerun Dolomite in the St. Francois Mountains province ranges in thickness from 45 to 160 ft, with the average thickness being approximately 120 ft. The lithology of the Derby-Doerun is a relatively chert-free dolomite with glauconite in the lower part. In many localities in this province, the unit also has significant amounts of grayish-brown shale throughout the formation.

The Derby-Doerun Dolomite is not a significant water-producing horizon in the St. Francois Mountains area. Where the unit is shaley, its permeability is greatly reduced. Even when the shale is absent, the rock exhibits poor water-yielding capabilities.

Potosi and Eminence Dolomites

The Potosi Dolomite, where present in the province, ranges in thickness from 260 ft to approximately 420 ft. It is not present in the restricted interior basins within the core of the Ozark Uplift; it occurs only near the outer boundaries of this province on the margins of the Precambrian knobs. The Potosi is composed of fine- to medium-crystalline, massive- to thickly-bedded, brownish-gray dolomite.

The unit is usually “vuggy,” with small cavities filled with quartz druse. When freshly fractured, the rock has an oily or bituminous odor.

The Potosi has excellent vertical and horizontal hydraulic conductivity and fairly uniform lithologic character. Since it is typically shallow in the St. Francois Mountains area, it is often within the zone of groundwater level fluctuation, and may not be permanently saturated. There are no high-yield wells in the province that produce only from the Potosi. However, many private domestic wells that are drilled into the Potosi use it for water supply. The Potosi in this setting is much like the Roubidoux Formation over much of the Salem Plateau province. It provides ample quantities of water for domestic purposes, but is not a high-yield aquifer until it is at a greater depth, and is well into the saturated zone.

Overlying the Potosi Dolomite, and the youngest unit in this area, is the Eminence Dolomite. The Eminence has a limited occurrence and is found only around the extreme perimeter of the province. Where present, the average thickness is about 75 ft.

It is doubtful that the Eminence yields significant quantities of water to any wells in the province due to its limited distribution, relatively small thickness, and typically high topographic position. Even where deeply buried and thickest, the unit does not generally yield large quantities of water.

Both the Eminence and the underlying Potosi dolomites exhibit extreme fracturing and weathering in the St. Francois Mountains province. Stresses produced by uplift of the Ozark Dome throughout geologic time have caused significant fracturing and faulting in rocks adjacent to the major part of the uplift. This greatly increased the vertical and horizontal hydraulic conductivities in the rocks in and adjacent to these structurally deformed areas. Subsequent groundwater movement along these areas of high permeability has produced deep weathering profiles and correspondingly thick mantles of residual material (figure 15). A high percentage of domestic wells drilled into the Eminence and Potosi dolomites in this area experience problems with mud seams and pockets.

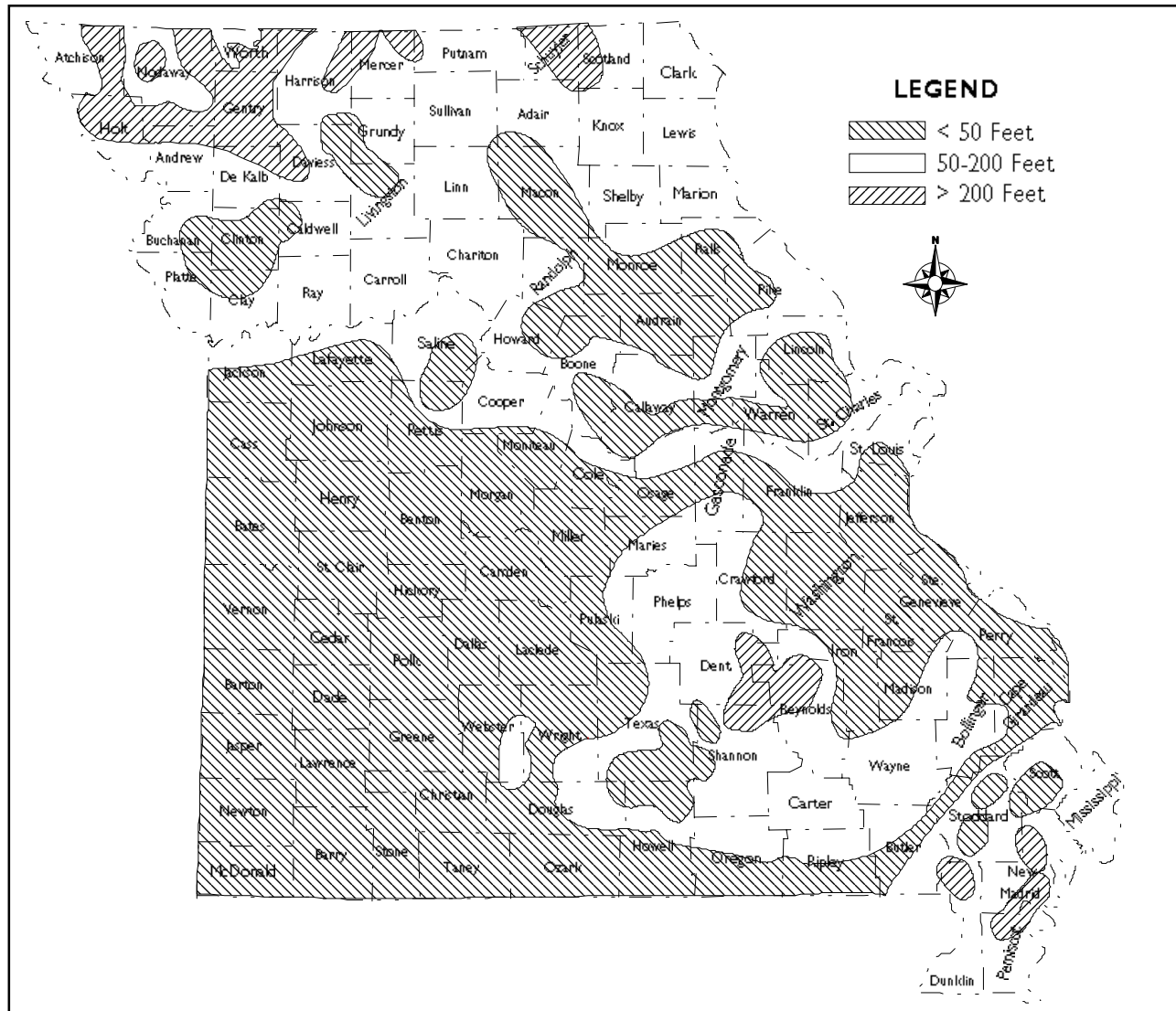


Figure 15. Generalized thickness of surficial materials in Missouri.

HYDROGEOLOGY

BASEMENT CONFINING UNIT

The Precambrian rocks in this region comprise the *Basement confining unit*. However, even though their permeabilities are generally very low, the Precambrian rock locally can yield small quantities of water. Groundwater production from the igneous rocks depends almost entirely on secondary permeability produced by fracturing. In some instances, where fractures are hydrologically connected with water-bearing zones in shallower, younger rocks or where the fracture

intersects some sort of surface drainage, the basement rocks will yield small quantities of water to wells. Precambrian rock forms the bedrock surface over an area of about 390 square miles, mostly in Iron, St. Francois, and Madison counties. Where the Precambrian is the surface bedrock unit or is found at shallow depths, residents are forced to either attempt to construct a well, or depend on cisterns and hauled water for their supply. When groundwater is encountered in the drilling of a "granite" well, the yields are usually less than five gallons a minute.

ST. FRANCOIS AQUIFER

The major aquifer available in this area is the St. Francois aquifer, which consists of the Lamotte Sandstone and overlying Bonneterre Formation. It crops out over a nearly 600-square-mile area in the St. Francois Mountains region, and is present in the subsurface throughout the Ozark Plateau except for a few places where it was never deposited or it has been removed by erosion. The St. Francois aquifer is bounded below by Precambrian igneous rocks that form the Basement confining unit. In places, where the Davis Formation is present, it forms an upper confining unit called the *St. Francois confining unit*. Locally, the St. Francois aquifer may be under water table or artesian conditions. Where present, it is used for private and public water supply throughout the St. Francois Mountains region, but is rarely used outside of the margins of this area.

The sediment-filled basins between the Precambrian knobs are the most reliable sources of groundwater in this province. The configuration of these basins, the saturated thickness of sedimentary rock deposited in them, and the lithology of the sediments are very important aspects to consider in determining the groundwater yield capabilities of proposed wells. In most instances, low vertical hydraulic conductivity greatly limits aquifer recharge. There is typically very limited horizontal circulation within the basins. Some appear to be hydrologically isolated with no obvious discharge points. The lack of groundwater circulation can cause an increase in the amount of dissolved solids. In other instances, adjacent basins are hydrologically connected, and groundwater moves between them. Wells drilled into the St. Francois aquifer in this area can locally yield as much as 400 gpm, but typically yield between 60 and 150 gpm.

The St. Francois aquifer in this province is estimated to contain about 919 billion gallons of usable groundwater in storage, or about 2.82 million acre-ft.

OZARK AQUIFER

The Ozark aquifer in the St. Francois Mountains area is typically unconfined and consists of the Potosi and Eminence dolomites. It can locally exceed 600 ft in thickness, but in most places is less than 300 ft thick. Due to its relatively high topographic and stratigraphic position, its saturated thickness is generally considerably less than its total thickness, and well yields are correspondingly low. The unit supplies numerous private domestic wells in the province but is not generally capable of supplying large quantities of water.

GROUNDWATER CONTAMINATION POTENTIAL

In some ways, the St. Francois Mountains province may be the most critical area in the state in terms of the need for groundwater protection. Other areas may have greater population densities and greater volumes of groundwater in storage, but none rely so much on groundwater for rural water supply and nowhere else is the cost of constructing rural water lines higher. The value of a resource is generally greatest where it is the most scarce, and nowhere in Missouri is groundwater more scarce than in the St. Francois Mountains. Because of the thin soils and igneous bedrock, it is also the most difficult region in Missouri for laying water lines. Groundwater will probably continue to supply most rural residents for the foreseeable future. Although vertical permeability in this region is not particularly high, contaminants on the surface will eventually reach the groundwater. Very slow circulation and a relatively small volume of groundwater leads to long residence time for contaminants and minimal dilution. Waste treatment facilities, landfills, and other potential sources of contaminants should be carefully sited in this province to avoid adversely affecting groundwater supplies.

THE SALEM PLATEAU GROUNDWATER PROVINCE

INTRODUCTION

The Salem Plateau is the largest physiographic subprovince of the Ozarks region, and the Salem Plateau groundwater province is the largest in the state. As its boundaries are drawn for this report, this area includes all or parts of 49 Missouri counties, with a total surface area of about 24,760 square miles.

The Salem Plateau contains two major regional aquifer systems—the shallower Ozark aquifer and the deeper St. Francois aquifer. The St. Francois confining layer hydrologically separates the two. The characteristics of each of the geologic units in this province will be discussed in ascending order, followed by a discussion of the aquifers and aquitards comprised by the formations. Since karst development has played such a dominant role in the creation of this landscape and has so greatly affected groundwater conditions, it, too, will be discussed.

GEOLOGY

Bedrock geologic formations underlying this province range in age from Upper Cambrian through Pennsylvanian. The Salem Plateau surrounds the St. Francois Mountains and is bounded to the west by the Springfield escarpment, to the southeast by the Ozark Escarpment, and to the north and east by the Missouri and Mississippi rivers, respectively. Table 4 is a detailed stratigraphic section showing the geologic formations discussed in this description of the Salem Plateau.

CAMBRIAN SYSTEM

Lamotte Sandstone

The oldest sedimentary rock formation and the deepest aquifer zone in this province is the Lamotte Sandstone. The Lamotte is Upper Cambrian (Croixian) in age, and rests unconformably on Precambrian basement rocks. The amount of relief and slope of this unconformable surface assures that both the thickness and dip of beds in the Lamotte are unpredictable, particularly around the margins of the St. Francois Mountains groundwater province. Its thickness ranges from approximately 100 ft along the margins of the St. Francois Mountain groundwater province to more than 300 ft in the western and southern parts of the Salem Plateau groundwater province. It averages about 200 ft. in thickness.

The Lamotte is predominantly a quartzose sandstone that locally, particularly near its base, grades into arkosic sandstone or conglomerate. The sandstone itself can range in color from almost white through shades of gray, and in some places can be dark brown and even red. Locally, sandy dolomite is present in the upper part and in some locations reddish shale is also present. The Lamotte crops out in only a few places in the Salem Plateau, but, with a few exceptions, is present in the subsurface throughout the region. In western Madison County, parts of Phelps, Crawford, and Pettis counties, the Lamotte is missing and younger Cambrian sediments rest unconformably on the Precambrian surface.

System	Series	Formation	Thickness (In Feet)	Lithologic Character	Hydrology	Remarks	
Recent		Loess & Residuum	0-300+	Windblown silt, and weathering products of limestone, cherty dolomite and dolomitic sandstone	Has fair permeability if materials jointed	Not a significant aquifer	
Pennsylvanian		Undifferentiated Pennsylvanian rocks	0-100	Thin limestones, shales, siltstones, sandstones, some coal beds	Small yields to wells. Water quality is usually poor	Locally a confining unit	
Ordovician and Mississippian undifferentiated		Undifferentiated Formations	0-400	Various lithologies: limestone, shale dolomite, thin sandstones	Locally yield small amounts of water to wells (3-5 gpm)	Not a significant aquifer	
Ordovician	Mohawkian	St. Peter Sandstone	10-100	Well-sorted, frosted, rounded quartzose sand, massive-bedded	Yields from 10 to 50 gpm	Ozark aquifer	
	Whiterockian	Everton Formation	0-120	Sandy, silty dolomite; clayey, dark gray shale	Not a significant aquifer		
	Canadian	Cotter Dolomite	200 (Avg)	Fine- to medium-crystalline, cherty dolomite with numerous green shale partings; some thin sandstone beds	5 to 15 gpm locally		
		Jefferson City Dolomite	200 (Avg)				
		Roubidoux Formation	170 (Avg)	Cherty, sandy dolomite and dolomitic sandstone; oolitic	15-35 gpm where shallow, 50-75gpm where deeply buried		
		upper Gasconade Dolomite	40 (Avg)	Massively-bedded, coarsely-crystalline, chert free dolomite	Yields 50 to 75 gpm		
		lower Gasconade Dolomite	250 (Avg)	Very cherty dolomite, algal reef zones in upper part			
		Gunter Sandstone Member	25-30 (Avg)	Sandstone and/or sandy dolomite	40 to 50 gpm - normal yield 200 to 500 gpm locally		
		Cambrian	Croixian	Eminence Dolomite	220 (Avg)		Medium to coarse-grained dolomite with low chert content
Potosi Dolomite	200 (Avg)			Fine- to medium-crystalline dolomite, with abundant quartz druse	Yields from 200 to 1000 gpm		
Derby-Doenin Dolomite	150 (Avg)			Fine-grained dolomite in upper part, shaley near base with glauconite	Yields of 30 to 50 gpm available locally in upper part, usually not a significant aquifer		
Davis Formation	180 (Avg)			Shale, siltstone, fine-grained sandstone, limestone and dolomite conglomerates	Not water bearing	St. Francois aquifer	
Bonneterre Formation	350 (Avg)			Fine- to medium-crystalline dolomite, sandy at base	Low yields, 10 to 15 gpm		
Lamotte Sandstone	100-300			Sandstone and dolomitic sandstone, Arkosic near base, locally absent	Moderate yields, 70 to 125 gpm		
Precambrian		Igneous & Metamorphic rocks				Basement Confining Unit	

Table 4. Stratigraphic section of the Salem Plateau groundwater province.

In the western and southwestern part of the Salem Plateau groundwater province, the Lamotte grades into or interfingers with a unit that is lithologically similar but finer-grained and was deposited under depositional conditions different than that of the Lamotte. This unit, the Reagan Sandstone, is water-bearing and would likely yield at least modest quantities of water, but has not been used as an aquifer. Thus, very little is known about its hydrogeologic characteristics.

Bonneterre and Davis Formations, and the Derby-Doerun Dolomite

The Bonneterre Formation is Upper Cambrian in age and conformably overlies the Lamotte Sandstone. It is a fine- to medium-grained dolomite and locally can be a limestone. It often contains thin shale layers or partings, but typically is a carbonate unit with a low clastic content. However, in the lower part, it appears that there is a gradational contact with the Lamotte, with alternating beds of dolomite and sandy dolomite; the sand increases towards the base of the Bonneterre. The Bonneterre has an average thickness in the Salem Plateau groundwater province of approximately 350 ft.

Overlying the Bonneterre and conformable with it, is the Davis Formation, also of Upper Cambrian-age. The Davis is composed of shale, siltstone, fine-grained sandstone, dolomite, and limestone conglomerate. The sandstone and siltstone have a large percentage of glauconite. Flat-pebble conglomerates are common in the Davis, and are one of the unusual features that characterize the unit in the outcrop area. The Davis has an average thickness of about 180 ft in the Salem Plateau groundwater province.

Overlying the Davis, and conformable with it, is the Derby-Doerun Dolomite. The Derby-Doerun is also Upper Cambrian-age, and is similar in composition to the underlying Davis. The chert content of the dolomitic portion of the unit is usually less than 10 percent, but the glauconite is almost always confined to the lower part of the formation and the dolomitic section is almost always in the upper 50 to 75 ft. The average thickness of the

unit in the Salem Plateau groundwater province is approximately 150 ft, although it may be absent locally.

Potosi Dolomite

The Potosi Dolomite of Upper Cambrian-age conformably overlies the Derby-Doerun Dolomite. The Potosi is composed of fine- to medium-grained, massive- to thickly-bedded brownish-gray dolomite. The unit is usually “vuggy,” containing small cavities that are commonly filled with quartz druse. Freshly fractured Potosi dolomite will exhibit an oily or bituminous odor. The unit is present in the subsurface throughout the Salem Plateau groundwater province with the exceptions of the areas in the western part of the province where it becomes gradational with the overlying Eminence Dolomite. It forms the bedrock surface in the area of the province surrounding the St. Francois Mountains groundwater province, and in this area, it is most usually covered with varying thicknesses of dark-red, residual clay and chert. The Potosi ranges in thickness from less than 30 ft, to as much as 400 ft, averaging about 200 ft. As with all of the formations in the Salem Plateau groundwater province, it dips or tilts away from the St. Francois Mountains, and the unit is deeply buried towards the outer margins of the Ozark Plateau.

Eminence Dolomite

The Eminence Dolomite is Upper Cambrian in age, and was the last formation to be deposited in Missouri during Cambrian time. It conformably overlies the Potosi Dolomite in the Salem Plateau groundwater province, and in the southwestern part of the Ozarks seems to interfinger with the Potosi Dolomite. This interfingering causes a repetition of the lithologies. A well drilled in Wright County for the city of Mansfield showed several repetitions of Eminence and Potosi lithologies.

The Eminence is a medium- to coarsely-crystalline dolomite unit. The formation contains a relatively small amount of nodular chert in approximately the upper 100 ft, while the lower part of the formation is relatively chert-

rock. The thickness of the lower Gasconade in the Salem Plateau groundwater province averages about 250 ft, but in the southeastern part of the province it thickens to almost 600 ft. Most of the Cambrian and Ordovician formations thicken as they dip or tilt to the southeast, into the Southeastern Lowlands.

The upper Gasconade Dolomite is a massively-bedded, medium-crystalline, light-gray dolomite that contains relatively small amounts of chert. Its thickness ranges from about 50 to 70 ft. The boundary between the upper and lower Gasconade is usually characterized by fossilized remains of large Cryptozoan algal reef masses. These algal reefs have been silicified, and now constitute massive chert beds that can be 10 to 20 ft thick. Because of its massive bedding, upper Gasconade typically forms cliffs where it crops out along valley walls. Its overall appearance, being relatively chert free, is in stark contrast to the very cherty, underlying lower Gasconade, and the very cherty, overlying Roubidoux Formation.

Roubidoux Formation

The Roubidoux Formation is Ordovician-age (Canadian Series), and consists of interbedded cherty dolomite, sandy dolomite and sandstone. In most places there is at least one sequence of sandstone in the Roubidoux, sandwiched between sandy and cherty dolomite. In some areas, however, there are two distinct sandstone sequences with cherty, sandy dolomite above, below, and between them. In a few locations, particularly in the Lake of the Ozarks area, the Roubidoux contains very little sand and is primarily a cherty dolomite.

The sandstone is composed of fine- to medium-grained quartzose sand that is usually rounded and frosted, much the same as modern beach sands. The cementing material binding the sand grains together is predominantly dolomitic, but there are areas where the sand is cemented by silica. On fresh, unweathered surfaces, the sandstone is creamy-tan to white. On weathered surfaces, the sandstone exhibits a range of color from brownish-gray, through all shades of brown, to yellow or even red. The dolomites are finely-

crystalline, brownish-gray and usually cherty. Outcrops of the dolomitic beds of the Roubidoux in the Salem Plateau groundwater province typically contain abundant chert nodules and generally weather to a dull reddish-brown. The sandstone, however, is the lithology by which the Roubidoux is best typified.

Secondary permeability in the Roubidoux is typically high and was likely developed by three processes. Initially, the carbonate part of the formation was probably limestone, but was later dolomitized; the recrystallization causes the volume of rock to decrease slightly, increasing permeability. The change in volume also affected the sandstone beds, causing fracturing in them. Finally, the formation was exposed to the effects of regional structural movement of the rocks, which caused additional fracturing.

Jefferson City and Cotter Dolomites

The Ordovician-age (Canadian Series) Jefferson City Dolomite conformably overlies the Roubidoux Formation and ranges in thickness in the Salem Plateau groundwater province from approximately 120 ft in the northern part to more than 350 ft in the southeastern part. Its average thickness is approximately 200 ft, and the formation generally underlies upland areas around the margin of the Salem Plateau. The Jefferson City is primarily a light-brown to tan, fine- to medium-crystalline, silty dolomite, with lesser beds of conglomerate, orthoquartzite, and shale. The shale is usually in the form of greenish-gray shale partings between the dolomite beds in the lower part of the formation. The unit has a lower chert content than the underlying Roubidoux. There is a conspicuous sequence of dolomite near the base of the formation where the dolomite is thickly- and massively-bedded. This zone has been used for dimension stone in the past, and is called the "Quarry Ledge."

The Cotter Dolomite is also Ordovician-age (Canadian Series), and conformably overlies the Jefferson City Dolomite. In the Salem Plateau, the unit generally occupies only high topographic settings, typically along major drainage divides such as between the Gasconade River basin and the White River basin. It

has lithologic characteristics similar to the underlying Jefferson City, but typically has a higher chert content, and contains more interbedded shale and sandstone. The lower part of the formation is relatively chert-free, which makes identification of the formation boundaries difficult. The average thickness of the Cotter is about 200 ft, and its maximum thickness of approximately 400 ft is reached in the southeastern part of the province where the Cambrian and Ordovician rocks thicken as they dip beneath the unconsolidated sediments of the Southeastern Lowlands.

Both the Jefferson City and Cotter dolomites contain zones of finely-crystalline, silty, chert-free dolomite that weathers to a light-tan color. These dolomitic zones have been termed "cotton rock" because of their appearance.

The Jefferson City and Cotter dolomites are sometimes difficult to differentiate at the outcrop. They also exhibit similar hydrogeologic properties. For these reasons, the units are usually considered as a single hydrologic unit, and will be discussed as such in this report.

Everton Formation

The Ordovician-age Everton Formation (Whiterockian Series) is the oldest formation in the Middle Ordovician and rests unconformably on underlying rocks, typically the Cotter Dolomite. It is composed of sandy dolomite, with locally interbedded sandstone and cherty limestone, but locally can contain considerable siltstone and shale. The area of occurrence for the Everton in the Salem Plateau groundwater province is in the extreme eastern part of the province in southern Jefferson, Ste. Genevieve, Perry and Cape Girardeau counties. However, this formation is not always present in the subsurface in its area of occurrence. The Everton in this province ranges in thickness from 0 to as much as 120 ft.

St. Peter Sandstone

The St. Peter Sandstone is Ordovician in age (Champlainian Series). It rests unconformably on the underlying Everton Formation, and where the Everton is com-

posed of sandstone the two units are difficult to distinguish from each other. Where it occurs, the St. Peter is from 10 to more than 100 ft of well-sorted, frosted and rounded, quartzose sand. The unit is predominantly silica, and in some areas is so pure that it has been extensively mined for silica for manufacturing glass. Unweathered exposures of the St. Peter are commonly pure white, with muted shades of pink and green. Weathered surfaces can be shades of brown, reddish-brown, and gray. The unit is massively-bedded, often with distinct bedding planes. Locally, the more massive beds exhibit cross-bedding, and ripple marks are not uncommon on bedding plane surfaces (Howe, 1961).

The St. Peter is present throughout the extreme northeastern and eastern part of the province. It crops out in a band from Franklin to Cape Girardeau counties, and is present at higher elevations in northern Gasconade County. Neither the St. Peter or Everton are regularly found in the northwestern part of the province. The exception being the localized occurrences of St. Peter preserved in paleo-sinkholes developed in the upper part of the Jefferson City and Cotter dolomites in Benton, Pettis, Cooper, and Moniteau counties.

Other Ordovician and Younger Formations in the Salem Plateau

Overlying the St. Peter Sandstone in the Salem Plateau groundwater province are several other rock formations. Their sequence of occurrence is highly dependent upon the area, and while they occur in one area, they may be missing in others. Mostly, they are present only in those areas where the St. Peter is present. They range in age from Ordovician through Mississippian and their combined thickness ranges from 0 to almost 400 ft.

Pennsylvanian Strata

Although not important as aquifers, Pennsylvanian-age rock in the Salem Plateau groundwater province have a pronounced effect on the quality of shallow groundwater in their outcrop area. Most of the Pennsylvanian strata in this area are shale or sandstone units. These rocks have a limited outcrop area

and form the bedrock surface at higher elevations in the northern part of the Salem Plateau groundwater province. In Osage, eastern Maries, extreme northern Phelps, northwestern Crawford, Gasconade, and western Franklin counties, the Pennsylvanian rocks rest unconformably on rocks of Lower Ordovician-age (mostly the Jefferson City and Cotter dolomites, but locally on the Roubidoux Formation). A small area in northeastern St. Louis County is also underlain by Pennsylvanian rocks. Pennsylvanian-age rocks are also preserved in paleo-sinkholes in several other surrounding counties to the west of the general outcrop area. Pennsylvanian rocks in the Ozarks are composed of fine- to medium-grained micaceous sandstone, clayey- to silty-shale, with thin, interbedded limestone.

In part of the outcrop area of the Pennsylvanian in the Salem Plateau groundwater province, fire clay deposits have historically been an important mineral resource. Fire clay was mined both south of the Missouri River, where Pennsylvanian strata unconformably overlie Ordovician rock, and in the Northeastern Missouri province north of the Missouri River in Callaway, Audrain, and Montgomery counties where the Pennsylvanian rests unconformably mostly on Mississippian rock. Pyrite (FeS) is locally associated with these deposits, particularly in the areas south of the Missouri River, where the deposits were of poor quality. Weathering and oxidation of the pyrite has locally caused an increase in dissolved iron and sulfate concentrations in shallow aquifer zones. High sulfate concentrations generally makes the water more acidic and corrosive to steel well casing and pump pipe. The high dissolved iron content in the water causes staining of laundry and plumbing fixtures, and the high sulfate content can give the water a bitter taste and cause intestinal problems. Casing is therefore used to exclude water from the Pennsylvanian strata in both private and public water supply wells in this area.

HYDROGEOLOGY

INTRODUCTION

Yields of wells drilled in the Salem Plateau are highly dependent on which geologic

units are encountered, and at what depths. In some instances, depth appears to be almost as important as the aquifer unit in this area. If a geologic unit is deeply buried, so that it is below the point in the rock column where all of the cracks, crevices and open space are permanently saturated, then it will usually produce moderate to large volumes of water to a well. If that same unit is encountered at a shallower depth in the zone where water levels can fluctuate seasonally due to changes in recharge volume, then the yields may be relatively small. If the unit is at or near land surface in a setting in which the recharge water is in transition, and there is little or no permanently stored water, it loses its importance as a water supply source.

The effects that bedrock depths can have on water well yields is illustrated by examples in the Roubidoux Formation in the Rolla area. A 200-ft deep well drilled into the Roubidoux Formation in the Rolla area will yield about 20 gpm. Here, the Roubidoux is at a relatively shallow depth, generally above the depth where it is completely saturated with water. South of Rolla, the Roubidoux is at land surface, and in many places the water table is below the base of the unit. Thus, in this shallow depth setting, the formation is not considered to be an important aquifer. However, in the southwestern part of the Salem Plateau groundwater province near the Arkansas border, the top of the Roubidoux is at a depth of more than 800 ft. Here, the potentiometric surface is several hundred feet above the top of the unit, and yields range from about 100 to 150 gpm.

The presence of geologic structures also can increase permeabilities, especially where fracturing of the bedrock is prominent. The same fracturing can present problems due to rapid introduction of recharge water carrying bacteria. Figure 17 is a map of the Salem Plateau groundwater province, showing yields of the various aquifer zones by location within the province.

Groundwater quality in the Salem Plateau groundwater province is generally good, with the exceptions being the very localized elevated radionuclides and mineralized water. Groundwater quality degrades along the

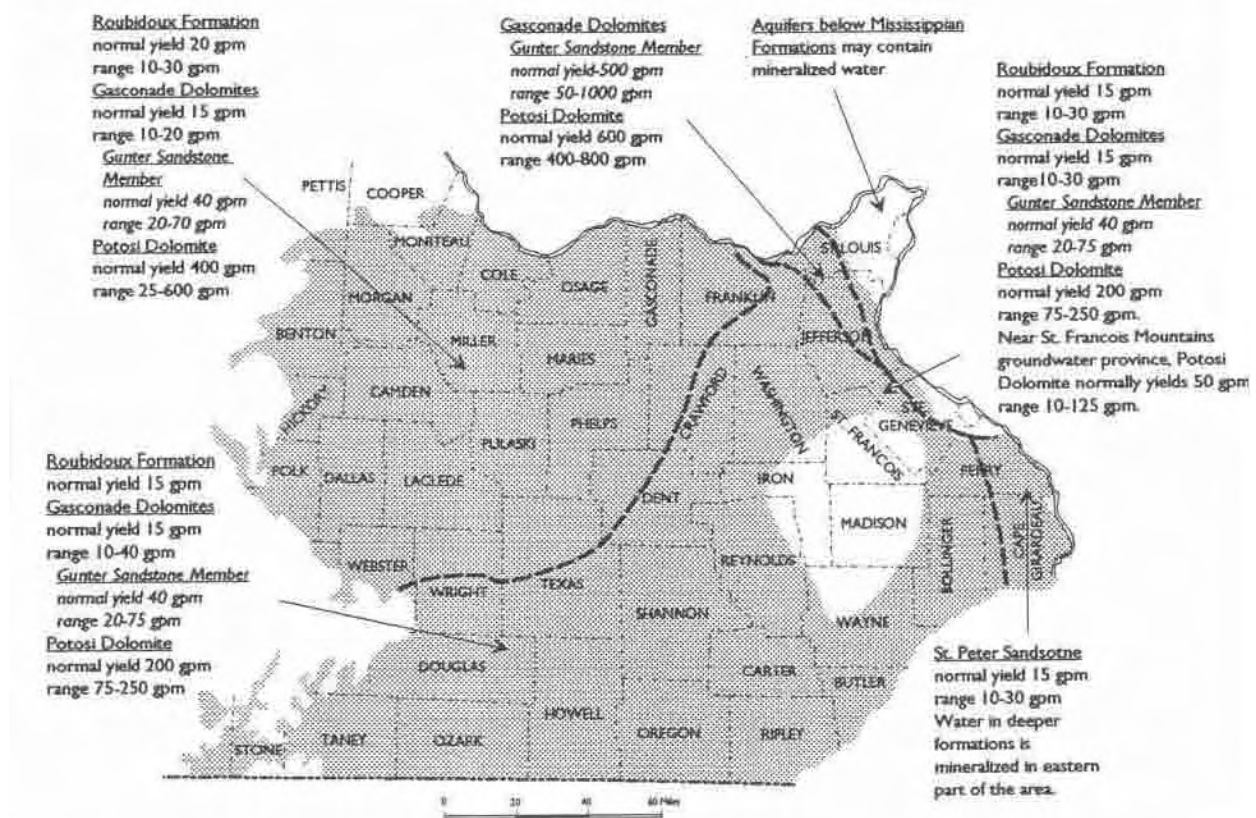


Figure 17. Yields of aquifers in the Ozark province (modified from Knight, 1962).

freshwater-salinewater transition zone along the eastern margin of the province and in the area in the north-central part of the province where shales and sandstones of Pennsylvanian-age are present. The Pennsylvanian rocks contribute waters which are high in both iron and sulfate. In most areas of the province, groundwater quality meets Missouri public drinking water standards with little or no treatment. The water is generally a moderately-mineralized calcium-magnesium-bicarbonate type. Chloride and sulfate are generally low except near the freshwater-salinewater transition zone.

St. Francois Aquifer

In the Salem Plateau, the Lamotte and Bonneterre formations comprise the St. Francois aquifer, which is the lowermost aquifer in the Ozark Plateau aquifer system. The St. Francois aquifer underlies all of the Salem Plateau, and almost everywhere is a

confined aquifer. It is usually considered a moderate-yielding aquifer in this region. Of the two formations comprising the St. Francois aquifer, the Lamotte Sandstone is responsible for most of the production. The Bonneterre typically has a low hydraulic conductivity, and yields only modest quantities of water. Depth to the top of the aquifer ranges from less than 500 ft near the St. Francois Mountains, to more than 5,000 ft in extreme eastern Missouri in Perry and Cape Girardeau counties.

Total aquifer thickness varies from less than 100 ft near Precambrian igneous highs to about 1,100 ft at the edge of the Ozark Escarpment. Thickness averages about 500 ft across the Salem Plateau (figure 18).

The St. Francois aquifer is confined above and below by formations of low-permeability. The Precambrian rocks underlying the Lamotte form the *Basement confining unit*. The Davis Formation and Derby-Doerun dolomites overlying the Bonneterre Formation form the *St.*

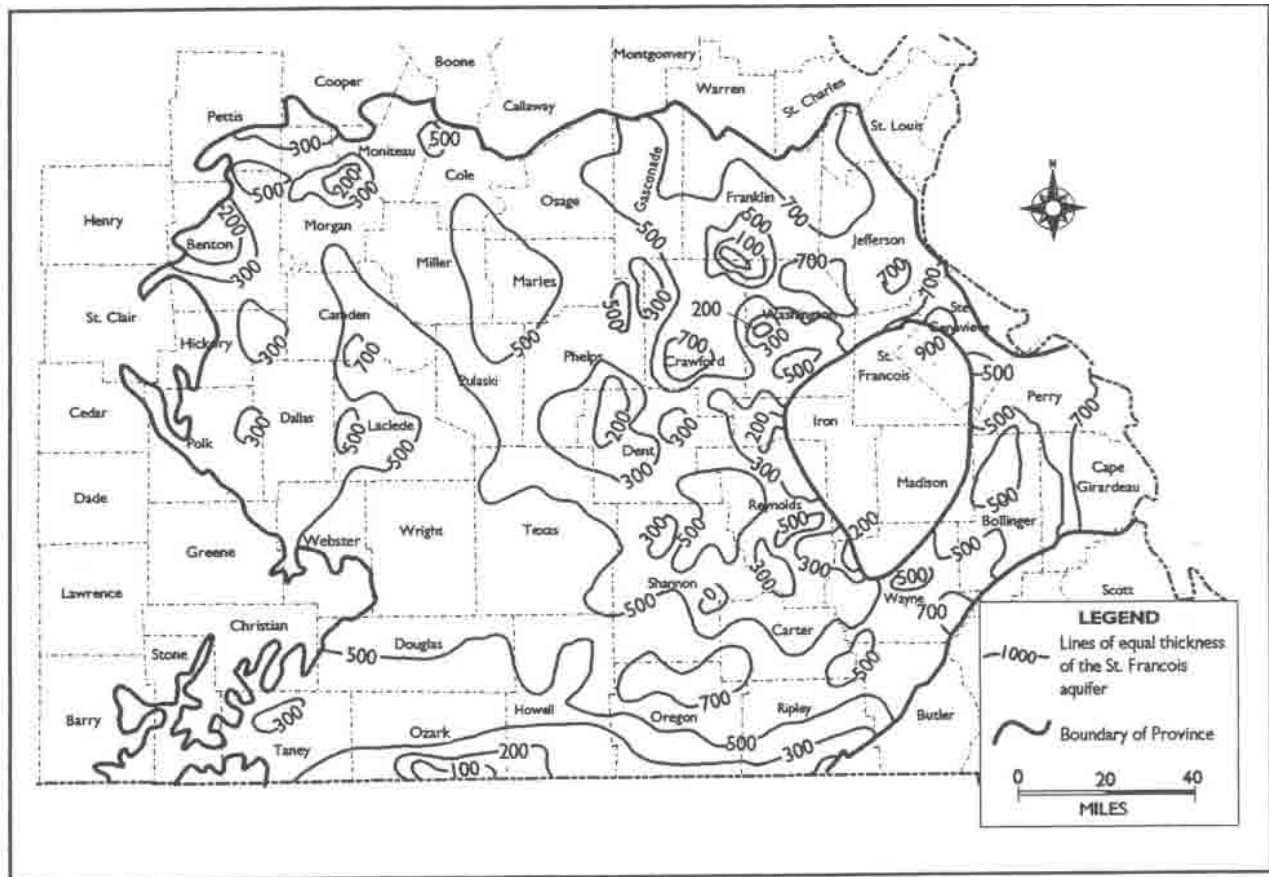


Figure 18. Thickness of the St. Francois aquifer in the Salem Plateau groundwater province (from Imes and Emmett, 1994.)

Francois confining unit. These confining units serve to separate the St. Francois aquifer hydrologically from the overlying Ozark aquifer. The presence of the St. Francois confining unit does not prevent water interchange between the two aquifers. It is, however, of low enough hydraulic conductivity that movement is greatly restricted.

The St. Francois aquifer, in the Salem Plateau, receives recharge from two general sources: down-dip movement of groundwater from the outcrop region in the St. Francois Mountains, and downward movement of water from the Ozark aquifer.

There are records of very few aquifer tests from wells producing only from the St. Francois aquifer, especially in areas other than the St. Francois Mountains. Thus, hydraulic conductivity and storativity information is scarce. Imes and Emmett (1994) used lateral hydraulic conductivity values of 1.6×10^{-4} ft/sec in the St. Francois Mountains area, and

8×10^{-5} ft/sec elsewhere, in developing a regional flow model.

Yields of wells producing from the St. Francois aquifer normally vary from 70 to 125 gpm. In areas like the eastern part of the Ozark province, adjacent to the east side of the St. Francois Mountains groundwater province, it is a very important aquifer because it is the only local source of groundwater available. Throughout much of the Salem Plateau, however, the St. Francois is not presently in use. The aquifer is penetrated by relatively few deep municipal wells. Most of the information on the Lamotte comes from mineral exploration borings where hydrogeologic information is normally not collected. A few towns in the province, including Rolla, Lebanon, and most recently Sullivan, have wells that are open to the St. Francois aquifer. However, the wells are also open to shallower aquifer zones, and the percentage of the total well yield provided by the St. Francois aquifer is rarely determined.

Several decades ago, before the hydrogeologic characteristics of the thick dolomite units in the Ozarks had been evaluated, it was commonly thought that only thick sandstones would yield the quantities of water necessary for municipal wells. Thus, the target zones for most of these wells were sandstone units such as those of the Roubidoux, Gunter, and Lamotte. Later, it was found that most of the production of these wells was from the dolomite units, and that production from the sandstones was generally minor in comparison.

Where both the Ozark aquifer and St. Francois aquifer are open to a well, it is possible that the Lamotte actually “robs” water from the shallower formations during non-pumping periods. The potentiometric surface of the shallower Ozark aquifer is generally above that of the Lamotte. Thus, there is the potential for down-hole water movement in the well bore when the well is idle.

Routine mine dewatering at several lead mines operating along the Viburnum Trend in Washington, Crawford, Iron and Reynolds counties accounts for much of the water produced from the St. Francois aquifer in the Salem Plateau. The Bonneterre Formation hosts the lead sulfide mineralization, and dewatering of the Bonneterre, while mining is occurring, causes the potentiometric surface of the St. Francois aquifer to decline several hundred feet in the mining area. In most cases, the St. Francois confining unit prevents draw-down from mine dewatering from affecting water levels in the overlying Ozark aquifer.

Locally, however, some dewatering of the Ozark aquifer has been experienced. One example occurred at the village of Bixby near the northern end of the Viburnum Trend. A large diameter ventilation shaft, referred to as Vent Shaft #50 by the Doe Run Company, was constructed about 1,000 ft northwest of the town. Such shafts are necessary for mine ventilation and generally do not cause problems. The vent shafts normally are not cased except through the surficial materials, and generally produce relatively small quantities of groundwater. Vent Shaft #50, however, encountered well-developed, solution-en-

larged openings in the Potosi Dolomite. Inflow from the shaft into the Casteel Mine more than 1,000 ft below the surface was initially several hundred gallons per minute.

The additional inflow into the mine did not hamper mining operations; the water was simply pumped back to the surface with the rest of the mine water, and discharged into a surface drainage. However, it caused a significant water-level decline in the Ozark aquifer in the Bixby area. Most of the private domestic wells in Bixby were relatively shallow, less than 200 ft deep, and produced from a very permeable zone in the Eminence Dolomite at a depth of about 150 ft. The permeable zone was dewatered by the vent shaft, and most of the private wells, though not dry, would no longer support sustained yields of more than about 3 gpm. Doe Run Company contractors grouted the bedrock around Vent Shaft #50, reducing the volume of water draining into the mine through the vent shaft to 50 to 70 gpm, and deepened the affected private wells to depths of about 600 ft to increase their yield and bore storage. Once the vent shaft was no longer needed, the Doe Run Company plugged it to totally halt the down-hole movement of water.

A water-level recorder was installed by the Division of Geology and Land Survey on a private well near Vent Shaft #50 in late 1987 (figure 19). Data collected from this well documents the water-level decline (figure 20). Vent Shaft #50 was plugged on September 5, 1991, and almost immediately water levels in the Ozark aquifer in the area began recovering. Full recovery of water levels to pre-Vent Shaft #50 conditions took about three and one-half years.

The natural quality of groundwater contained in the St. Francois aquifer in the Salem Plateau is usually quite good, at least where the unit is used for water supply. However, since it is not widely used outside of the St. Francois Mountains groundwater province, its water quality throughout most of the region is conjectural. The water is usually of a calcium-magnesium-bicarbonate type with low total dissolved solids. Its hardness is typically considerably lower than waters from overlying dolomitic aquifer units. Total dissolved

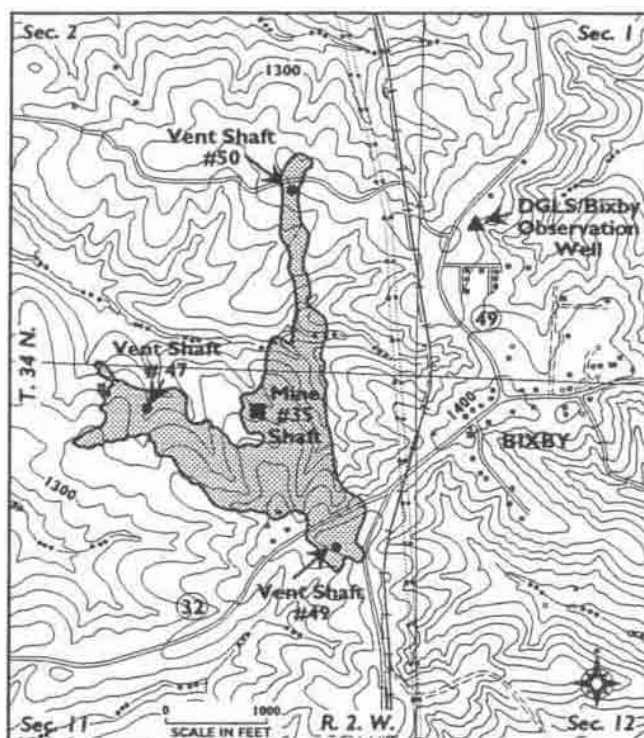


Figure 19. Location of Vent Shaft #50 in relation to Bixby and Bixby observation well. Shaded area is the approximate extent of Mine #35 (the Casteel Mine) in 1988.

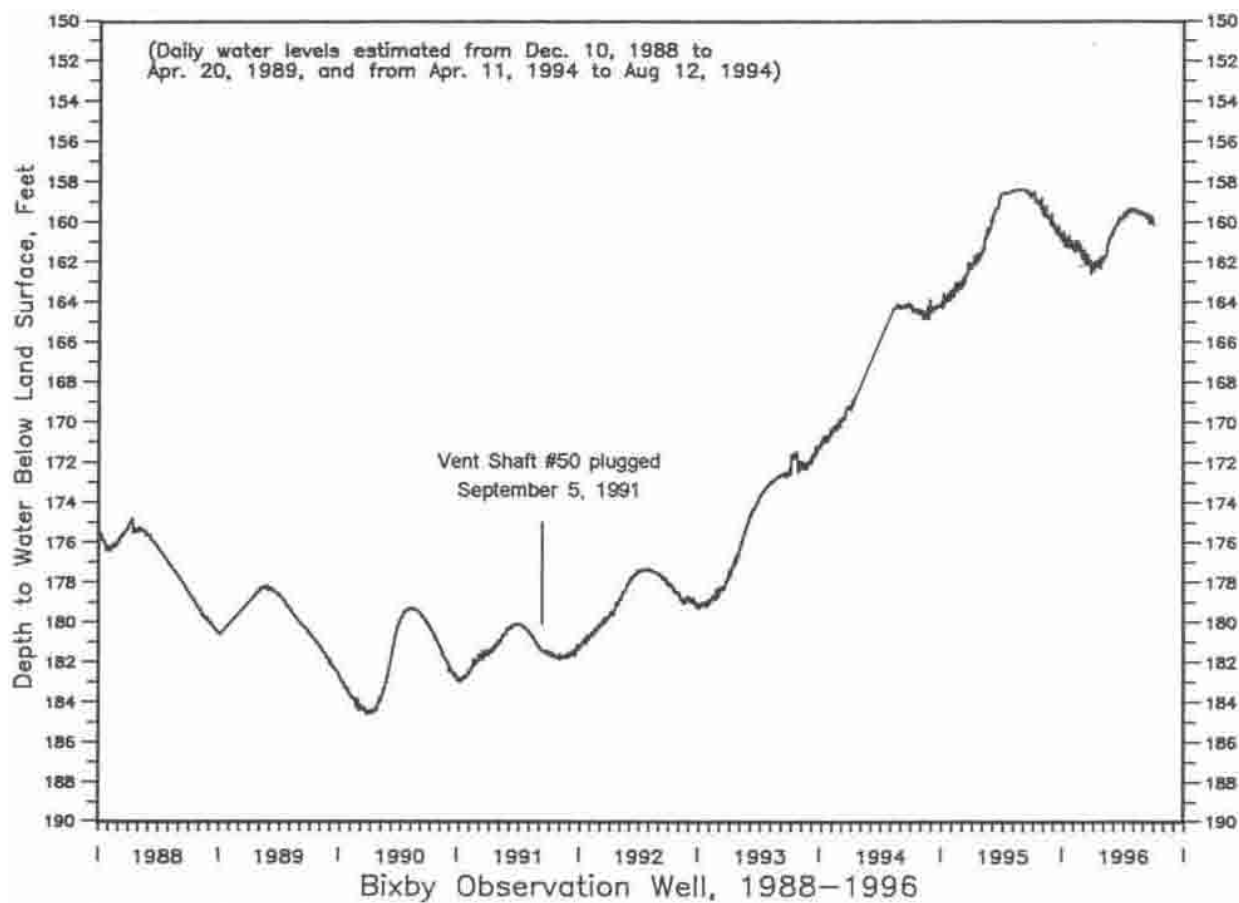


Figure 20. Groundwater-level hydrograph, Bixby observation well, Iron County.

solids likely increase greatly near the freshwater-salinewater transition zone, but data are not sufficient to substantiate this.

The Salem Plateau, along the St. Francois Mountains, has undergone periodic tectonic movement numerous times in the geologic past. The epeirogenic upwarping related to uplift of the Ozark Dome caused fracturing and faulting of the Paleozoic sedimentary rocks. Where the Lamotte has been extensively fractured, and those fractures filled with clay, water quality has suffered. In many instances, dissolved iron in the water may exceed 0.3 mg/l, the maximum recommended level for public water supplies. On the east side of the St. Francois Mountains groundwater province there are localized water quality problems caused by naturally occurring radionuclides. Gross alpha, radium-226 and radium-228 activities in this area are locally above the maximum levels that can be approved for public supplies. Currently these levels are 15 picoCuries per liter for gross alpha, 5.0 picoCuries per liter radium-226 and radium-228 combined.

In other areas of the state, higher concentrations of radionuclides are associated with geochemical reactions. Such reactions take place along the freshwater side of the freshwater-salinewater transition zone. The reactions appear to be controlled by the oxidation/reduction potential, which in turn may be related to elevated concentrations of hydrogen sulfide gas. However, this does not seem to be the case for the occurrence of high radionuclides in the Lamotte bordering the St. Francois Mountains. The freshwater-salinewater transition zone is some miles to the east, and there is no hydrogen sulfide present. In this case, the probable source of the increased radionuclides is the weathering of certain granites in the igneous complex of the St. Francois Mountains to the west. Small quantities of radioactive material derived from weathering of certain types of igneous rocks in the St. Francois Mountains were transported toward the east, and deposited with the sands of the Lamotte, probably in the lower, arkosic part of the formation.

Locally, the Lamotte is extremely fractured and the fractures can contain large quantities of silt and clay. This is also an area where the formation can have numerous thick shale sequences in the upper part. When wells encounter them, either of these conditions can cause a serious problem in the integrity of the drill hole, the total production of the well, and in the quality of the water produced. If the Lamotte is the only producing aquifer in the area, such problems may require abandoning the hole and choosing another well site.

Many private domestic wells are completed in the Lamotte Sandstone where it occurs at a shallow depth. Most of these supplies are located near the boundary between the Salem Plateau groundwater province and the St. Francois Mountains groundwater province where other aquifers are not available. Since a large volume of water is seldom needed for a private domestic well, most of them do not fully penetrate the Lamotte. Thus, yields of private wells producing from the Lamotte generally range between 25 and 40 gpm, and are typically much lower than those of fully penetrating, larger-diameter municipal wells. The Bonneterre is commonly used for private domestic supplies in the Ozark province adjacent to the St. Francois province where it is encountered at relatively shallow depths. Yields of 10 to 15 gpm are possible. The Bonneterre has a low chert content. Fracturing in chert-rich formations greatly enhances the permeability of the unit. The Bonneterre is a relatively pure dolomite or limestone, and fracturing does not seem to have greatly increased the secondary permeability, perhaps because it is more deeply buried and has not been subjected to karstification as have the shallower carbonate units. Yields of wells producing from the Bonneterre are therefore typically low, which greatly limits the formation's use. Although numerous public water supply wells are open through the Bonneterre, few if any produce only from it.

The St. Francois aquifer in the Salem Plateau groundwater province is estimated to contain about 23.7 trillion gallons, or about 72.7 million acre-ft of usable groundwater.

ST. FRANCOIS CONFINING UNIT

The St. Francois confining unit, which forms the upper boundary of the St. Francois aquifer throughout most of the Salem Plateau, consists of shale, siltstone, dolomite and limestone. Formations comprising the confining unit are, in ascending order, the Davis Formation and the Derby-Doerun dolomites. The St. Francois confining unit is saturated, but its hydraulic conductivity is generally so low that it yields little water. A notable exception to this is found in the area southwest of Lebanon in Laclede County near the town of Phillipsburg. Here, the Derby-Doerun Dolomite contributes 30 to 50 gpm to several public water supply district wells. In addition, the wells producing from the Derby-Doerun near the St. Francois Mountains yield modest quantities of water. In most areas, however, it yields little and is considered part of an aquitard.

The thickness of the St. Francois confining unit in the Salem Plateau range from 100 ft to about 500 ft, and averages about 200 ft. Shale content ranges from zero to about 30 percent, and averages about 20 percent (Imes and Emmett, 1994).

OZARK AQUIFER

Undoubtedly, the most important aquifer in the Salem Plateau is the Ozark aquifer. Nearly every town, city, and rural water district produce most, if not all, of their water from this aquifer. It also is tapped by the vast majority of private domestic wells. The most water-productive zones within the aquifer are the St. Peter Sandstone, Roubidoux Formation, lower Gasconade Dolomite, Gunter Sandstone Member and the Potosi Dolomite. Although water-bearing and considered part of the aquifer, the Cotter and Jefferson City dolomites have relatively low hydraulic conductivity as does the upper Gasconade Dolomite.

The Ozark aquifer crops out throughout the Salem Plateau. Its thickness varies considerably due to erosion, generally ranging from 200 ft near the St. Francois Mountains to as much as 3,000 ft along the Arkansas border near the Bootheel. Normal thickness in most of the province is from 800 to 1,000 ft (figure 21).

The Ozark aquifer in the Salem Plateau is recharged by precipitation. Residual soils formed by the weathering of the mostly carbonate bedrock are very permeable. In addition, the surface and subsurface weathering of the carbonates has created numerous karst groundwater-recharge features such as sinkholes and losing streams that allow very rapid movement of water from the surface into the subsurface. Average yearly recharge rates vary from a few inches to as much as 14 inches per year.

Potentiometric measurements show a prominent regional groundwater divide in the Ozark aquifer that roughly trends east-west through the southern part of the Salem Plateau. Generally, hydraulic conductivities are higher north of the groundwater divide (Imes and Emmett, 1994).

The Potosi Dolomite is undoubtedly the most prolific and reliable aquifer zone in the Salem Plateau, and is the target unit of choice for many community public water supplies and other high-yield wells. Locally throughout this province, such as at Rolla, wells drilled through the Potosi yield 800 to 1,000 gpm. Because of the way that most wells are drilled in the Ozarks, with several aquifer zones open to the well, not all of the water is from the Potosi. Even so, yields from the Potosi likely range from 200 to 500 gpm. In its outcrop area, or in areas where it occurs at shallow depth, the unit yields only moderate amounts of water, generally 20 to 30 gpm. But where there is a significant thickness of saturated rock above it, yields increase dramatically.

The aquifer test depicted in Figure 22, city of Rolla's Hypoint Industrial Park well #2, shows the drawdown of the well over the period of the test plotted against time. Using standard pump-test analysis techniques, the transmissivity of the well was calculated to be 19,000 gallons per day per foot (gpd/ft). The higher the transmissivity, the better the water-yielding capabilities of the well. Table 5 shows transmissivities for wells penetrating the Potosi Dolomite at selected cities in the Salem Plateau province. In all cases, these wells also penetrate aquifer zones above the Potosi and water is produced from several zones.

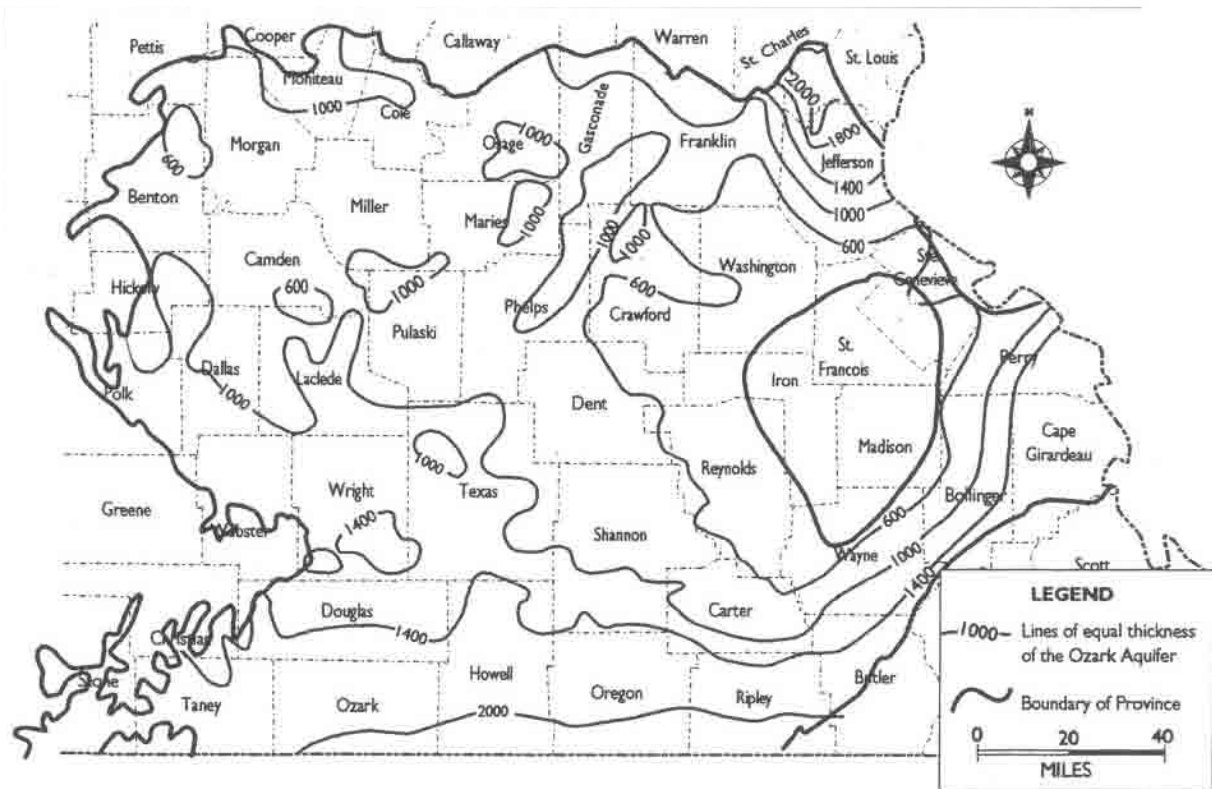


Figure 21. Map showing thickness of the Ozark aquifer in the Ozark province (modified from Imes, 1990).

Another measure of the ability of a well to yield water is its *specific capacity*. This is a measure of the gallons of water per minute being pumped, divided by the amount of drawdown produced by pumping (gpm/ft.). In most instances, Potosi wells yield almost twice as much water per foot of drawdown, as do wells finished in shallower aquifer zones.

Yields of 50 to 75 gpm are available from the upper part of the Eminence throughout the province, principally due to secondary permeability developed along fractures that are common in the unit. In areas where the formation is overlain by a relatively thick sequence of saturated rock, its yield usually increases. Yields from 150 to 250 gpm are not uncommon if the total thickness of the unit is used. One of the puzzling aspects of the Eminence is the fact that the unit usually shows a large amount of solutionally-enlarged fracturing, yet yields of water are fairly modest, as noted from the figures given above.

Considering the thickness of the unit and the amount of secondary porosity from solution-enlarged openings, the Eminence should be a major water-yielding zone, but even where the unit is deep enough to be fully saturated it still yields only a maximum of about 250 gpm. Several factors probably contribute to the relatively low yields of the unit. The fractures, though abundant, may be discontinuous and may not have a high degree of interconnection. Evidence of this is found in the Current and Eleven Point river basins where there are numerous caves developed in the Eminence, and where most of the major springs discharge from the Eminence. Obviously, the Eminence in these areas contains bedrock openings large enough to channel flow to Missouri's largest springs, but yields of wells drilled into the Eminence near these same springs are not particularly high. The relatively low chert content of the Eminence could account for part of this. In other aquifer

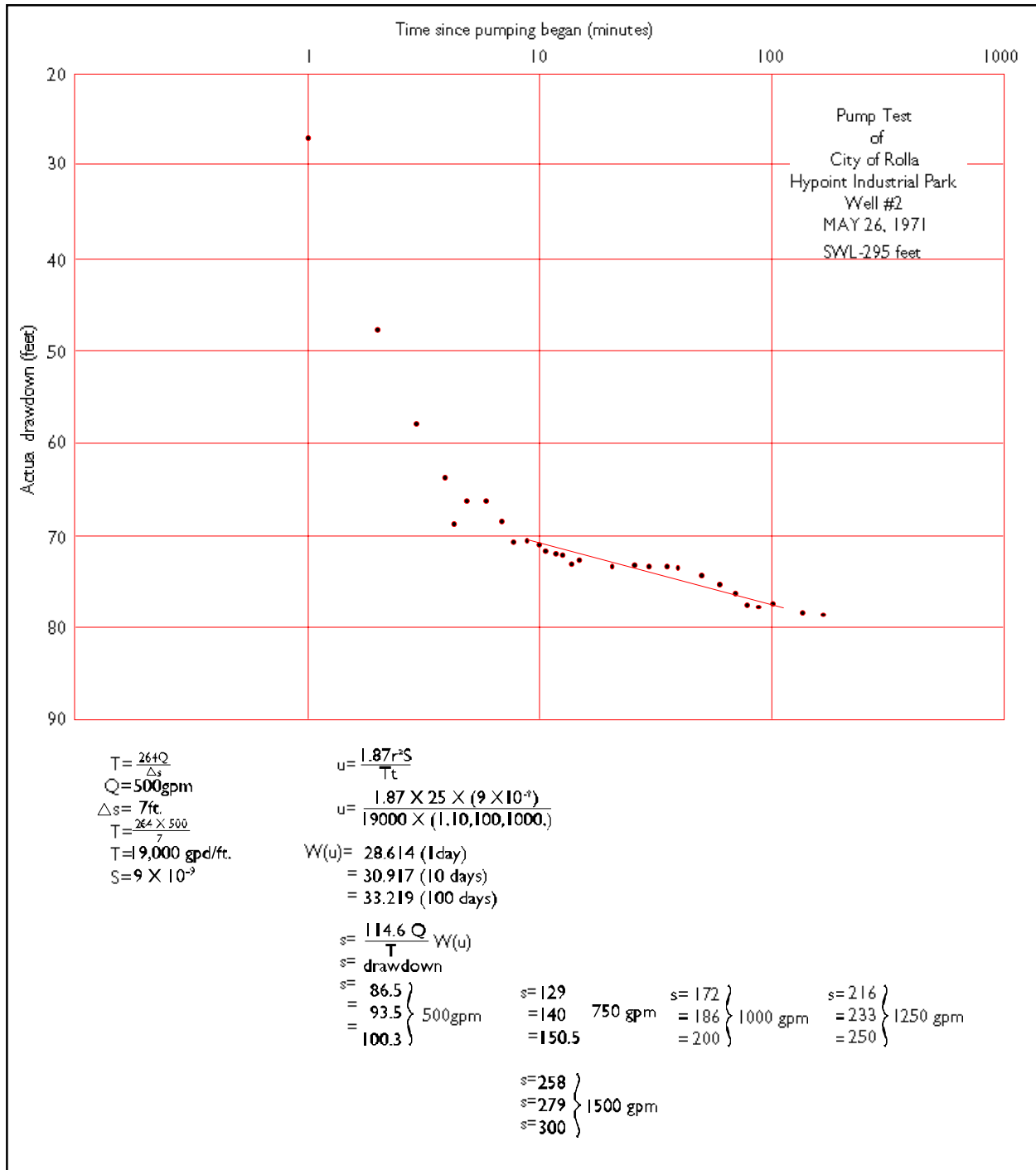
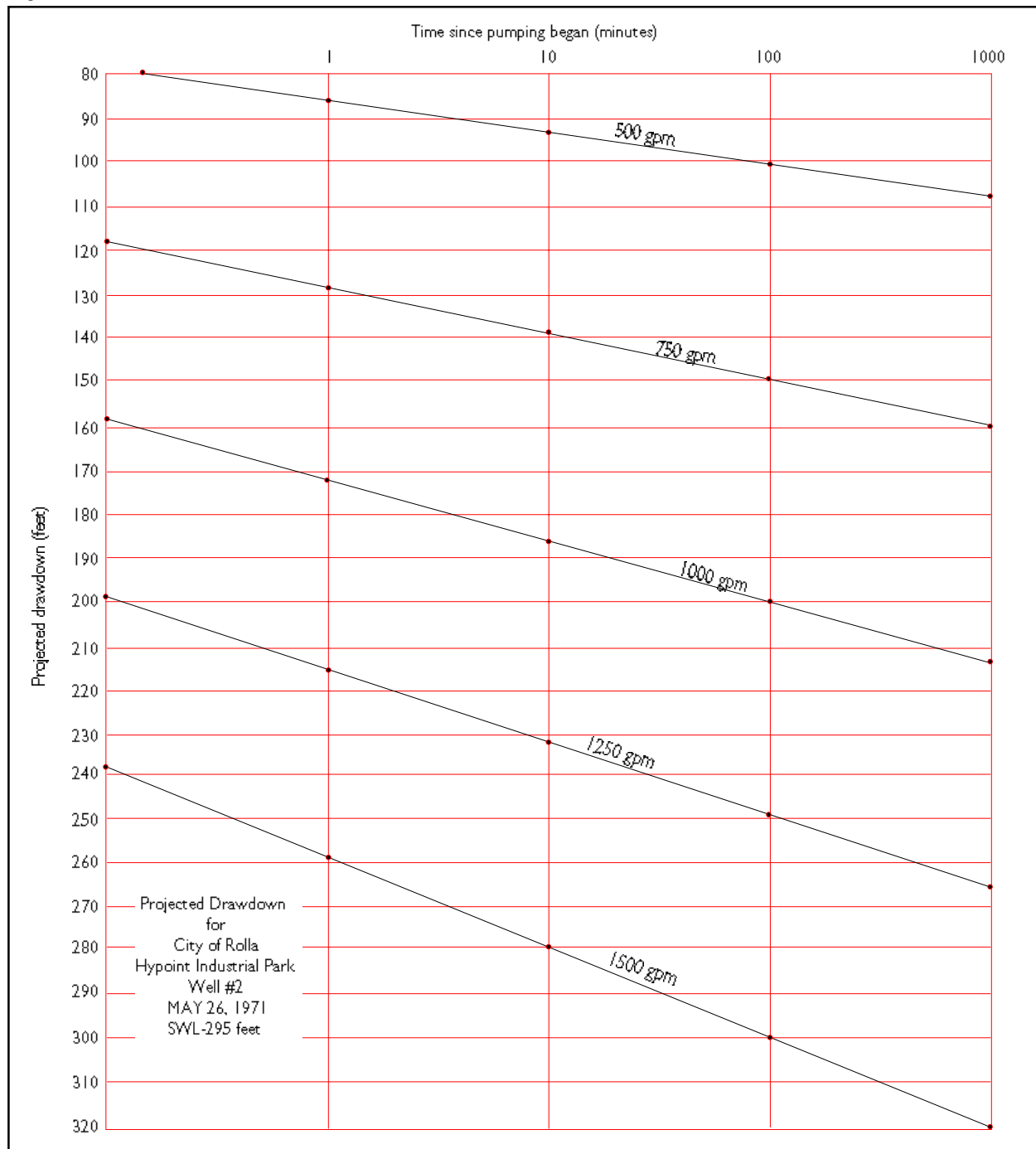


Figure 22. Pump test and time-drawdown projections for Rolla's Hypoint Industrial Park well #2.

units where chert is abundant, the chert fractures more cleanly than pure dolomite, and is less likely to be dissolved. The dissolution of dolomite not only produces residual material that can restrict groundwater flow if it is depos-

ited in fractures, but the resulting poor circulation also can elevate the level of dissolved carbonate material that, if redeposited, can further restrict flow. Also, since chert beds lie in a horizontal plane, and fracturing is normal-

Figure 22 continued.



ly near vertical, the presence of thick chert zones could allow better interconnection between fractures.

Until about 1994, high-yield community wells in the Branson area in Taney County typically bottomed in the upper part of the Eminence Dolomite, and produced mostly from the lower Gasconade Dolomite and

Gunter Sandstone Member. Typically, these wells yielded 300 to 500 gpm, and were from 1,100 to about 1,500 ft deep. Taney County is at the very western edge of the Salem Plateau groundwater province, and depth to the Potosi Dolomite here is considerably greater than in the eastern part of the province. At the time they were installed, the yields of these wells

Well Owner	County	Location Sec. T. R.	Yield (gpm)	Transmissivity gal/day/ft	Storage Coefficient (dimensionless)
Lost Valley Hatchery Well #1	Benton	04 40N 22W	450	4,604	1.6×10^{-4}
City of Camdenton Well #6	Camden	25 38N 17W	500	3,568	NA
Church Farm #7	Cole	18 45N 12W	100	573	2.0×10^{-4}
Cole Co. PWSD #1 Well #3	Cole	18 44N 12W	570	16,217	1.6×10^{-3}
MO State Penitentiary Well #2	Cole	08 44N 11W	260	5,280	1.5×10^{-3}
City of Cuba Well #4	Crawford	30 39N 04W	300	7,900	1.0×10^{-3}
City of Buffalo Well #2	Dallas	23 34N 20W	350	6,160	1.5×10^{-3}
Dent Co. PWSD Well # 1	Dent	29 34N 05W	150	1,460	NA
City of Sullivan Well #10	Franklin	10 40N 02W	200	2,400	NA
City of Union Well #2	Franklin	27 43N 01W	608	34,151	NA
City of Hermann Well #3	Gasconade	26 46N 05W	350	1,270	3.0×10^{-3}
City of West Plains Well #8	Howell	18 24N 08W	420	2,464	NA
Jefferson Co. PWSD #7 Well B	Jefferson	26 41N 04E	323	101,000	6.6×10^{-3}
Laclede Co. PWSD #1 Well #3	Laclede	12 33N 17W	140	3,800	2.0×10^{-4}
Laclede Co. PWSD #3 Well #6	Laclede	07 33N 18W	225	2,970	NA
City of Belle	Maries	21 41N 07W	145	2,000	1.0×10^{-3}
Ozark Co. PWSD #1	Ozark	18 22N 15W	150	5,800	2.0×10^{-3}
Tyson Foods Well #2	Pettis	22 46N 22W	950	7,838	2.0×10^{-3}
Rolla Industrial Park Well #2	Phelps	32 38N 07W	500	19,000	9.0×10^{-9}
City of St. James Well #4	Phelps	19 38N 06W	550	12,000	2.5×10^{-4}
City of Rolla Well #13	Phelps	07 37N 07W	802	13,233	NA
Ft. Leonard Wood Well #2	Pulaski	09 35N 11W	200	2,640	NA
Ft. Leonard Wood Well # 8	Pulaski	04 35N 11W	250	1,375	1.2×10^{-4}
Eastern MO Corr. Fac. Well #2	St. Louis	05 43N 03E	350	27,600	NA
Texas Co. PWSD #1 Well #2	Texas	27 33N 11W	180	2,500	NA
City of Licking Well #3	Texas	07 32N 08W	300	4,300	3.0×10^{-4}
Cabool Industrial Park	Texas	10 28N 11W	200	4,800	4.0×10^{-3}

Table 5. Hydrologic characteristics of selected Ozark aquifer wells in the Salem Plateau groundwater province.

were adequate to meet demands of the area and there was no need to attempt drilling into the Potosi Dolomite. In addition, data concerning depth, yield, and water quality of the Potosi were lacking, so there was some risk in attempting production from the deeper zone. Rapid growth in the Branson area in the late 1980s spurred interest in tapping into the potential of the Potosi, and in 1994, two wells with depths in excess of 2,000 ft were drilled. Both of these wells were considered successful. Yields in both exceeded 800 gpm and water quality was excellent. Since then, several other wells have been drilled into the Potosi in the Branson area. As this area continues to develop, it is likely that the Potosi will become an increasingly important target zone for groundwater development.

Since recharge to the Potosi is primarily from leakage or movement of water from shallower aquifer zones, there is very little difference in chemical quality between it and the shallower aquifer zones. Table 6 shows chemical analyses of selected municipal wells completed in the Potosi in the Salem Plateau groundwater province. However, since all of these wells are open to other water-producing formations, the water quality is not exclusively that of the Potosi Dolomite. Water quality from the Potosi is quite good throughout the Salem Plateau, except near the freshwater-salinewater transition zone in the northeastern part of the Ozarks province (figure 9). In this area, even water in some of the shallower zones can be locally mineralized. Throughout the Salem Plateau groundwater province, circu-

City Water Supply	pH	Alkalinity	Iron	Manganese	Sodium	Potassium	Calcium	Magnesium	Nitrate	Sulfate	Chloride	Fluoride	Total Dissolved Solids	Total Hardness	Copper
Cabool	7.6	238.	< 0.10	< 0.02	3.1	1.0	50.2	30.5	0.14	10.0	2.0	1.10	297.0	251.0	< 0.01
Desoto	7.3	279.	< 0.10	< 0.02	2.8	1.1	60.0	37.2	0.05	29.0	3.0	0.11	358.0	303.0	0.01
Festus	7.7	269.	< 0.10	< 0.02	4.8	1.6	62.8	33.2	0.05	25.0	3.0	0.39	313.0	294.0	0.01
Hermann	7.6	215.	< 0.10	< 0.03	3.1	1.8	42.1	25.8	0.05	15.0	4.0	0.16	244.0	211.0	< 0.01
Iberia	7.4	276.	< 0.10	< 0.02	1.9	1.6	60.0	34.6	0.05	13.0	2.0	0.20	329.0	292.0	0.01
Lebanon	7.6	207.	0.50	< 0.02	2.6	1.4	40.8	22.7	0.16	15.0	3.0	0.20	221.0	195.0	0.04
Licking	7.7	165.	< 0.10	< 0.02	1.7	1.2	35.0	19.8	0.14	10.0	2.0	0.10	208.0	169.0	0.01
Mansfield	7.6	211.	< 0.10	< 0.02	2.8	1.1	45.9	24.8	0.08	10.0	5.0	1.20	264.0	217.0	0.02
Rolla	7.5	277.	< 0.10	< 0.02	3.1	1.1	52.9	38.5	0.05	42.0	2.0	1.10	325.0	291.0	0.08
Salem	7.7	210.	< 0.10	< 0.02	2.2	0.7	42.8	25.1	0.38	< 10.0	2.0	< 0.10	251.0	210.0	0.01
Sullivan	7.9	141.	< 0.10	< 0.02	3.5	0.8	29.8	19.5	0.19	27.0	6.0	0.10	195.0	155.0	< 0.01
Washington	7.5	234.	< 0.10	< 0.02	2.3	1.1	35.8	33.9	< 0.05	15.0	3.0	0.10	248.0	220.0	0.02

Table 6. Chemical analysis of water from selected Ozark aquifer wells in the Salem Plateau groundwater province (from Department of Natural Resources, 1991).

lation of waters from shallower to deeper horizons is relatively rapid, and recharge from precipitation is continually moving fresh water through the flow system.

The Gunter is a target zone for many high-yield public water supply, irrigation and industrial wells in the Salem Plateau groundwater province. In some cases yield from the lower Gasconade Dolomite and Gunter Sandstone Member is ample to meet a particular need, but typically the well produces from other zones besides the Gunter. Many private domestic wells use the Gunter for water supply in the Lake of the Ozarks area of Camden, Miller and Morgan counties. Its shallow depth, moderate yield, and good water-quality makes it an excellent zone for private domestic wells. This is also the area where sand content is highest, and the unit is easy for local drillers to recognize. Yields of 15 to 40 gpm are not unusual from the Gunter in this area. In most instances where domestic wells use the Gunter for a water supply, higher-yielding community or noncommunity wells will have casing set and grouted to depths that exclude the Gunter. It is also possible, particularly in the Lake of the Ozarks area, for the Gunter to contain water which might be contaminated by private on-site waste disposal systems.

In most areas of the Salem Plateau, the Gunter Sandstone Member contains less than 30 percent sandstone, and is a sandy dolomite or dolomite. However, there seems to be no correlation between the sand content and well yields in the Gunter. In fact, yields of 400 to 500 gpm are possible in some locations where the Gunter contains only sandy dolomite.

The Gasconade Dolomite throughout most of the Salem Plateau groundwater province is the target zone for many wells. Wells drilled into the upper part of the lower Gasconade, have excellent reliability during prolonged drought periods. Yields of 50 to 70 gpm are possible from this sequence of rock where it is buried deep enough to be in the permanently saturated zone. However, where the unit is relatively shallow, it generally yields from 25 to 40 gpm. Although data are sparse, toward the outer boundaries of the province where the Gasconade is 700 ft below land surface or deeper, it may yield as much as 200 gpm.

Although the Gunter Sandstone Member and the lower Gasconade Dolomite are typically high-yielding zones, the upper Gasconade generally is not. Where appropriate, the casing of many high-yield wells is set to the base of the upper Gasconade. The hydraulic conductivity of the unit is not low enough for

it to be considered an aquitard, but it does have a substantially lower hydraulic conductivity than the lower Gasconade and the overlying Roubidoux Formation.

The Gasconade Dolomite crops out along most of the major valleys in the Salem Plateau and hosts many karst features including sinkholes, losing streams, caves and springs. Groundwater recharge commonly occurs at higher elevations where losing streams are developed in the Gasconade Dolomite. Where the Gasconade forms the valley walls and bottoms along major rivers, it typically hosts springs. Almost all of the first magnitude springs in the Ozarks discharge either from the Gasconade or Eminence dolomites. Many Ozark streams with well-sustained base flows, even during periods of drought, owe their flow characteristics to groundwater additions from the Gasconade. Where the Gasconade underlies upland areas in the Ozarks, it may host losing streams and sinkholes. Caves are commonly developed in the Gasconade Dolomite throughout the Salem Plateau.

The Roubidoux Formation is likely the most widely used single aquifer zone for private domestic water supply in the Salem Plateau. Thousands of private wells used for domestic and farm water-supply produce wholly or principally from the Roubidoux. Where the Roubidoux is deep enough to be permanently saturated, and is overlain by 100 ft or more of Jefferson City Dolomite, its water quality is generally not adversely affected by surface activities. However, where the unit is at or very near land surface, its saturated thickness may be insufficient to supply the needed amount of water during drought periods.

Yields of domestic wells 250 to 350 ft deep that are drilled into the Roubidoux, range from 15 gpm to about 35 gpm in the Salem Plateau groundwater province. Higher yields are more likely in wells drilled into the Roubidoux near the western and southwestern boundaries of the province. Here the formation is more deeply buried and permanently saturated, and normally yields 50 to 100 gpm.

The high secondary permeability typically found in the Roubidoux can be both a

favorable and unfavorable characteristic. Where the Roubidoux is sufficiently deep to preclude the effects of surface activities, its high permeability makes it a good-yielding aquifer zone. However, where the Roubidoux is at or very near land surface, it can easily be affected by contaminants. Where the unit is exposed to the surface in upland areas it is often deeply weathered, and can contain mud and clay zones, openings and broken rock. This is particularly common in a large area of southeast Missouri extending from the Ozark Escarpment at the northern end of the Bootheel to near Rolla, and west to near U.S. Highway 63.

Losing streams are commonly developed where the Roubidoux Formation underlies valleys. Surface-water flow is lost to the subsurface in many stream reaches that cross the outcrop of the Roubidoux. Of all the losing stream reaches in the Ozarks, an estimated 60 percent of them are in areas where the stream channel is developed in the Roubidoux Formation (Bill Duley, 1995; personal communication). The water may resurface at a spring some distance downstream in the same drainage, or it may be diverted in the subsurface to a spring in an adjacent drainage basin. Interbasin transfer of groundwater through karst groundwater systems is common in the Ozarks.

Aquifer contamination in the Roubidoux is a local concern. Since the unit has relatively high vertical and horizontal permeability, and crops out over a large area of the Salem Plateau, the possibility of contaminants entering the formation and traveling for some distance is a distinct possibility. This type of aquifer vulnerability is a concern for all of the Salem Plateau groundwater province due to the degree of karst development, but the problem is more serious with the Roubidoux due to its hydrogeologic characteristics than with most other bedrock units. Contaminant migration in the Roubidoux depends greatly on the type of contaminant and the mechanism by which it was introduced into the subsurface. Water-soluble contaminants introduced into the Roubidoux through losing streams, sinkholes, or other discrete recharge features, will generally follow well-defined

flow paths through bedrock conduits. While the contaminant may cause serious water-quality problems at the spring where the water resurfaces, groundwater adjacent to the conduit between the spill site and spring is largely unaffected. Groundwater moves quickly through conduit systems, often more than one mile per day. Fortunately, once the contaminant sources are removed, water-quality normally improves quickly.

Contaminants from such things as poorly sited septic tank drain fields and lagoons in upland areas generally move more slowly when introduced into the Roubidoux in diffuse recharge settings. Depending on the degree of bedrock fracturing and the permeability of the sandstone beds, the contaminants may travel in a plume that increases in width and depth as distance from the contaminant source increases, or the contaminants may enter solution-enlarged fractures and follow a well-defined flow path. Because of slower groundwater velocities and lower recharge rates in diffuse recharge settings, contaminants introduced into the groundwater system here may cause longer-term groundwater-quality deterioration. In nearly all cases, contaminants that are not soluble in water will cause longer term groundwater-quality degradation, whether they are introduced into an aquifer through sinkholes or losing streams, or enter as diffuse recharge.

Although both the Jefferson City and Cotter dolomites are considered aquifer units, both typically exhibit relatively low vertical and horizontal hydraulic conductivities. They are not considered aquicludes, but can function locally as leaky aquitards. In upland settings where the Jefferson City and Cotter dolomites are the shallowest bedrock units, the amount of vertical groundwater movement through them into the underlying Roubidoux Formation is much less than where the Roubidoux forms the bedrock surface. Another indication of low vertical permeability in the Jefferson City and Cotter dolomites is the low-flow characteristics of streams flowing on them. Streams, which have their headwaters in upland settings where the Jefferson

City and Cotter are the shallowest bedrock unit, typically gain flow or at least maintain flow to where they flow across the underlying Roubidoux Formation. At this point, many streams will lose flow into the Roubidoux, and except during periods of very wet weather, the reaches of streams on the Roubidoux will be dry for several miles. The streams may become gaining streams as they flow across the underlying Gasconade Dolomite. Ponds or small impoundments constructed in areas where the Cotter-Jefferson City is at the surface usually hold water, while the same structures constructed where a weathered Roubidoux Formation underlies the lake site may leak badly. Exceptions exist where the Roubidoux weathers to a plastic, clay-rich residuum. In these locations, water retention structures constructed in the Roubidoux are much less likely to leak. Water loss may also occur because of faulting or structurally induced fracturing of the rock units, which will not only cause the stream to lose water, but may also provide subsurface channels that route the water to some distant point of resurgence. Conversely, some faults are tightly cemented, which, instead of enhancing it, forms a barrier to groundwater movement.

The high topographic position that the Jefferson City and Cotter dolomites typically occupy, and their low hydraulic conductivities, combine to limit water infiltration, storage, and yield of water. Neither are considered important water-supply sources in most of the Salem Plateau. The exception to this is in the areas around the perimeter of the Salem Plateau where the units are thickest, and along topographic highs such as the interfluvium between the White River tributaries and the Gasconade River in Wright, Douglas, Texas and Howell counties. Here, older private domestic wells locally produce from the Jefferson City and Cotter. The combined thickness of the formations in some of these areas exceeds 300 ft, and though yields are modest, generally 5 to 10 gpm, they are adequate to meet most domestic needs.

Two other geologic formations—the Powell and Smithville—are present at the ex-

treme northeast and southeast corners of the province and their geologic and hydrologic characteristics are very similar to the Jefferson City and Cotter dolomites. Because of their limited distribution, and their relatively poor water-yielding characteristics, they are not considered important aquifers. These units are, in ascending order, "Powell" Dolomite and Smithville Formation. They are conformable with the underlying formations and are the uppermost units in the Ordovician System (Canadian Series). Where the "Powell" and Smithville are relatively thick and water saturated, water yields are similar to those of the Cotter and Jefferson City.

Although water-bearing and capable in most areas of yielding modest quantities of water, the Everton is not considered important as an aquifer. In fact, the unit commonly presents problems for well drillers constructing wells into the deeper, high-production zones in the underlying Ordovician and Cambrian rocks. The Everton is composed of dolomite, sandstone and shale. Its heterogeneous lithology sometimes makes it necessary for well drillers to set casing through the unit to prevent sediments from caving into the well bore and affecting the quality of the produced water. Where the Everton occurs at relatively deep depths, casing depths of more than 500 ft may be necessary.

The St. Peter is the uppermost aquifer zone in the Salem Plateau province that can reliably yield more than 10 gpm. Yields of 10 to 50 gpm are possible from the St. Peter where the unit is moderately thick. Many private domestic wells use the St. Peter for water supply in the eastern and northeastern parts of the Salem Plateau groundwater province where younger, shallower formations yield only very small amounts of water. This is especially true in those areas adjacent to the freshwater-salinewater transition zone where deeper bedrock aquifers yield highly-mineralized water. Where the St. Peter occurs at depths in excess of 400 ft and deeper aquifers yield good-quality water, high-yield public water supply wells are often cased above the St. Peter to allow it to contribute production to the

well. The St. Peter has a very limited areal extent in the Salem Plateau, and is found only along the northern and eastern margins of the province.

Water quality in the St. Peter is generally good. Total dissolved solid content of water from the St. Peter is generally less than from the underlying carbonate rocks, and the water generally contains less calcium and magnesium, thus is "soft" compared to the deeper water. However, in the vicinity of the freshwater-salinewater transition zone, the unit locally contains water that is high in radionuclides. On the north and east sides of the freshwater-salinewater transition zone, it contains water with total dissolved solids in excess of 1,000 mg/L.

The Ozark aquifer in the Salem Plateau groundwater province is estimated to contain about 208 trillion gallons of water, or about 639 million acre-ft. This represents nearly 42 percent of Missouri's usable groundwater.

OTHER AQUIFER ZONES IN THE SALEM PLATEAU GROUNDWATER PROVINCE

Rocks younger than St. Peter Sandstone crop out in a band paralleling the Mississippi River in the extreme eastern part of the Salem Plateau groundwater province. South of the Ste. Genevieve fault zone in Perry and Cape Girardeau counties these include the Joachim Dolomite, Plattin Limestone, Kimmswick Limestone and several other Ordovician-, Silurian-, and Devonian-age rock units. Some of these formations do not yield any appreciable water while others may yield enough water to supply a private domestic well. Locally, the Joachim and Plattin can yield modest quantities of water ample for most domestic needs, but none of these units typically yield large quantities of water. North of the Ste. Genevieve Fault Zone, Mississippian-age strata form the bedrock surface throughout extreme eastern Ste. Genevieve and Jefferson counties, and throughout much of St. Louis County. Some Mississippian-age formations, including the Salem, St. Louis, and Burlington-Keokuk limestones, are capable of yielding several gallons of water per minute to domestic wells.

St. Louis County, though not generally considered part of the Ozarks, is discussed as part of the Salem Plateau groundwater province in this report. In extreme western and southern St. Louis County, the Ozark aquifer yields potable water; however, the quality of water in zones below the St. Peter Sandstone deteriorates to the northeast. The quality of water in the St. Peter remains potable for another few miles to the north and east, but then it too becomes too highly mineralized for use. In much of the central, eastern, and northern parts of the county, only the Mississippian-age limestones including the Burlington-Keokuk, Salem and St. Louis limestones, (collectively called the post-Maquette aquifer) yield usable quality water.

GROUNDWATER-FLOW CHARACTERISTICS OF THE OZARK AQUIFER IN THE SALEM PLATEAU

The direction of shallow groundwater movement in the Salem Plateau is controlled by many factors. In the absence of karst development, flow in the shallower units is usually controlled by topography with the elevation of the potentiometric surface being highest along watershed divides and lowest along streams. In this instance, groundwater movement will be toward local drainage. Deeper circulation of groundwater is generally dependent on the regional dip of the rocks. Throughout most of the Ozarks, deeper flow is away from the structural center of the Ozark Uplift, or away from the St. Francois Mountains. The velocity and volume of groundwater flow is dependent on the vertical and horizontal hydraulic conductivities of the rock units, and the hydraulic gradient.

Although primary permeability accounts for some groundwater movement, secondary permeability provided by faulting, jointing, fracturing and the dissolution of carbonate rock has had a far greater impact on present day hydrologic conditions in the Salem Plateau. Most of the rock units in the Salem Plateau are composed primarily of dolomite. However, not all dolomite units readily develop appreciable secondary permeability, and some zones or formations transmit water at

faster rates than others. The rock units that have developed considerable secondary permeability become important aquifers where they are deep within the saturated zone. Areas with thick mantles of residuum appear to have higher recharge rates than those with lesser thicknesses. The storage capacity of thick residuum is relatively high, and this helps to provide more sustainable recharge to the underlying bedrock aquifer zones than in areas where the residuum is thin.

Regionally, the Ozark aquifer in the Salem Plateau is considered unconfined since it does not have a confining unit overlying it. However, several characteristics of the aquifer cause it to be locally confined or semiconfined in the deeper zones. Generally, lateral hydraulic conductivity in most of the Ozark aquifer is considerably higher than vertical hydraulic conductivity. Thus, if all other factors are equal, the rate of horizontal water movement is greater than the rate of vertical water movement. Also, certain formations in the aquifer, or zones in certain formations, have characteristics that are more similar to aquitards than to aquifers. Parts of the Cotter and Jefferson City dolomites and the upper Gasconade Dolomite have much lower vertical and horizontal hydraulic conductivities, than units above and below, and locally can be leaky aquitards. In essence, a thick, heterogeneous aquifer such as the Ozark aquifer consists of relatively permeable horizontal zones separated by less permeable zones.

The variations in hydraulic conductivity within the aquifer are largely responsible for the changes in water level with depth within the aquifer. In regional recharge settings, such as along major surface-water drainage divides, water-level in the aquifer increases with depth, indicating downward water movement. Wells completed in relatively shallow zones may have water levels more than 100 ft higher than wells cased through the shallow zones and completed in deep zones. Where groundwater is discharging from the aquifer the opposite is generally true. This is most often seen along major streams such as the Gasconade, Osage, Current, and North Fork rivers. Here, water

levels in deep wells drilled in valley bottoms generally stand several feet above those of shallow wells, indicating ascending water and discharge from the aquifer into the stream. In many cases, relatively deep wells drilled in this setting will be flowing artesian wells.

There is commonly a perception of mysticism concerning flowing artesian wells. Actually, these wells occur wherever the potentiometric surface of the aquifer that the well penetrates is above land surface. To most people, the term artesian means that water is flowing from a well onto land surface. Strictly speaking, artesian conditions simply mean that the potentiometric surface of an aquifer is above the top of the aquifer. The water level of a well drilled into an artesian aquifer will be above the top of the aquifer, but will not necessarily be above land surface. The groundwater is under some artesian pressure provided by a head differential between the point where recharge to the aquifer occurred and the well. This head difference may be the result of dipping rocks, structural deformation of the rock units, or simply the result of leaky, overlying aquifers providing abundant water to the lower aquifers through permeable vertical connections only a short distance away.

Deep groundwater circulation has been documented numerous times at various places in the Ozarks. For many years, the Division of Geology and Land Survey maintained a groundwater-level monitoring well at West Plains in Howell County. This monitoring well was equipped with a Stevens A-35 water-level recorder that continuously measured and graphically displayed changes in groundwater levels. The recorder was installed on a public water-supply well that was no longer used by the city. This well, drilled in 1914, is 1,305 ft deep and contains 800 ft of pressure-grouted casing. The casing excludes production from the Jefferson City Dolomite, Roubidoux Formation, and most of the Gasconade Dolomite. Producing formations below the casing are the Gunter Sandstone Member, Eminence Dolomite, and upper Potosi Dolomite. Municipal wells for the city of West Plains are cased much deeper than most pub-

lic water-supply wells in Missouri. The exceptionally deep casing is needed to help prevent shallow recharge from directly entering the wells every time there is measurable precipitation. Despite 800 ft of casing, groundwater levels will rise as much as 200 ft within a few hours after a major rainfall event in the area, and the wells will produce water containing microorganisms that are characteristic of surface water and rapidly recharged groundwater (figure 23).

Ordinarily, there should be no way for recharge to circulate to the deeper zones this quickly, particularly with all of the shallow zones excluded from the well. The type of karst development that occurs in this area is likely the factor controlling the rapid vertical water movement. From a few miles south of Willow Springs, through West Plains, to Thayer, is a band of intense karst development several miles wide. Throughout this area the bedrock has been deeply weathered, leading to the development of thick residuum, many losing streams, and numerous large sinkholes. One of the largest sinkholes in Missouri, Grand Gulf, is near at the southern end of this area near Thayer. Even more interesting is the fact that the karst development is mostly in the Cotter and Jefferson City dolomites that in most other places do not commonly host extensive karst development. The nearly instantaneous water-level changes and rapid introduction of microorganisms are most likely the result of the pressure head increase in the shallow aquifer zones being transmitted to deeper zones because of the high degree of vertical permeability in the aquifer here.

The seasonal fluctuation of groundwater levels throughout southern Missouri directly relates to the recharge and discharge characteristics of the aquifers, and the volume of groundwater produced by area wells. Water levels may rise as much as 15 to 20 ft from late fall to early summer in response to recharge provided by precipitation, and decline through the late summer and fall when recharge is lacking and water use is generally highest. In the fall, after vegetation becomes dormant and temperatures lower, both evaporation

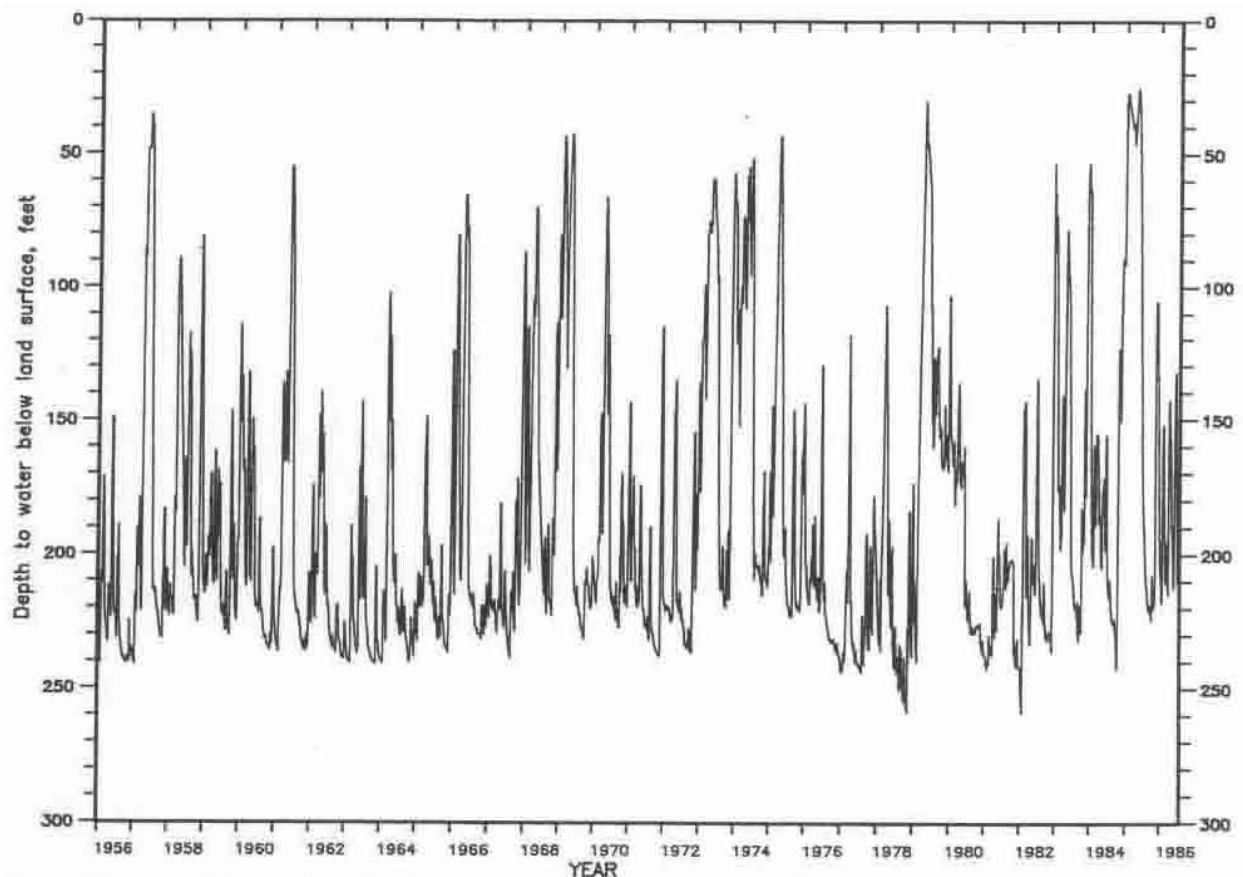


Figure 23. Groundwater-level hydrograph, city of West Plains well #2, Howell County.

and transpiration decrease. With a decrease in these losses, a greater percentage of precipitation becomes groundwater recharge. In the spring, when vegetation begins growing, there is more plant transpiration and temperatures rise, causing more evaporation. Also, the rainfall events during the summer tend to be of shorter duration and more intense, causing more rapid runoff and less infiltration of the water, therefore water levels tend to decline.

The direction that groundwater flows and its rate of flow are controlled by several factors. As with surface water, groundwater will flow from areas of higher head potential to areas of lower head potential. In the shallower, water-bearing zones that have not been appreciably altered by karst development, topography commonly controls the direction of flow; groundwater will flow toward stream valleys or to some point of lower elevation. If the recharge occurs in an upland area, water may flow along the top of a clay

pan or fragipan and exit on a hillside as a wet-weather seep. Or, it may move vertically through more permeable residual soil, through smaller unsaturated openings in the shallow bedrock until it reaches the water table, and then move horizontally to a resurgent point at a nearby spring or in a gaining reach of some local stream. Depending on vertical hydraulic conductivity in the formations, part of the recharge may find its way into the deeper, more productive aquifer zones. The rate of flow is dependant on the hydraulic conductivity of the water-bearing material, and the hydraulic gradient. If the hydraulic gradient is essentially flat, then groundwater moves very little even in very permeable materials. Groundwater velocities are greatest in permeable materials where there is an appreciable hydraulic gradient.

The direction of flow in the deeper aquifer zones is controlled primarily by the regional dip or tilt of the formations. As stated in an

earlier section of this report, all of the rocks dip away from the Ozark Dome; deep groundwater movement is controlled by this structure to a large extent, and flow is away from the axis of the dome. Rate of flow in the deeper horizons is much slower than in the shallower zones, but is still controlled by the amount of dip of the rock.

THE EFFECTS OF KARST DEVELOPMENT ON GROUNDWATER MOVEMENT

The most significant geologic condition that influences groundwater recharge and movement in the Salem Plateau is the presence of karst features. Karst is a term used to describe an area where the dissolving of soluble bedrock has led to the formation of a variety of features such as caves or other underground drainage conduits, sinkholes, solutionally enlarged crevices, losing streams, springs, and other less common features. Karst features can generally be categorized into groundwater recharge, groundwater transport, and groundwater discharge features.

Sinkholes

Sinkholes and losing streams are the two most common karst groundwater-recharge features in the Salem Plateau. Sinkholes, which are topographic depressions formed by the dissolution and subsurface removal of the earth materials, are common in many areas of the Salem Plateau, predominately in upland settings. In some areas of the Salem Plateau, particularly between West Plains and Thayer, and in the counties of Perry and Ste. Genevieve, sinkholes drain areas of several square miles or more. The sinkhole drainage areas in eastern Perry and Ste. Genevieve counties generally consist of hundreds of sinkholes developed within larger sinkhole plains. Within the boundaries of these sinkhole plains essentially all of the runoff is funneled into the subsurface; there is no surface-water outflow. Between West Plains and Thayer in southeastern Howell and southwestern Oregon counties, there are numerous large sinkholes. Some of these sinkhole basins are large enough to topographically resemble surface drainages;

however, the drainages end in large depressions where the water must enter the subsurface. The largest of these is Grand Gulf, the focal point of Grand Gulf State Park about five miles west of Thayer in Oregon County (figure 24). Grand Gulf is a collapsed cave that forms a sinkhole more than one mile long. The collapse captured the flow of Bussell Branch, a surface watershed containing nearly 20 square miles of drainage. Bussell Branch is a losing stream, and only provides inflow into Grand Gulf after heavy rainfall. However, the uncollapsed part of the cave, which continues at the downstream end of Grand Gulf, is sufficiently choked with mud and organic debris so that after heavy rainfall the sinkhole will flood to the depths of more than 100 ft for periods of several weeks. Water entering Grand Gulf reappears within a few days at Mammoth Spring, Arkansas' largest spring, about eight miles to the southeast (Vineyard and Feder, 1982).

Losing Streams

Losing-stream segments are common throughout the Salem Plateau. It is not uncommon to see a well-developed stream valley and channel that transports surface flow only after major rainfall events. In most instances, there is no surface flow in losing-stream watersheds until the alluvial materials become saturated and the solution-enlarged bedrock openings that channel water into the subsurface can no longer channel all of the flow underground. Surface flow is generally sustained for periods of a few hours to a few days, until it recedes to where the bedrock openings can again accept all of the water and channel it into the subsurface. Some streams contain both losing and gaining reaches. Flow may be lost into the subsurface in a losing segment, while groundwater from seeps of springs may provide flow in another gaining reach. In some places the flow that is lost into the subsurface in an upstream losing reach reappears at a spring in the downstream gaining reach of the same valley, but it is not uncommon for flow to be diverted through the subsurface to a different drainage.

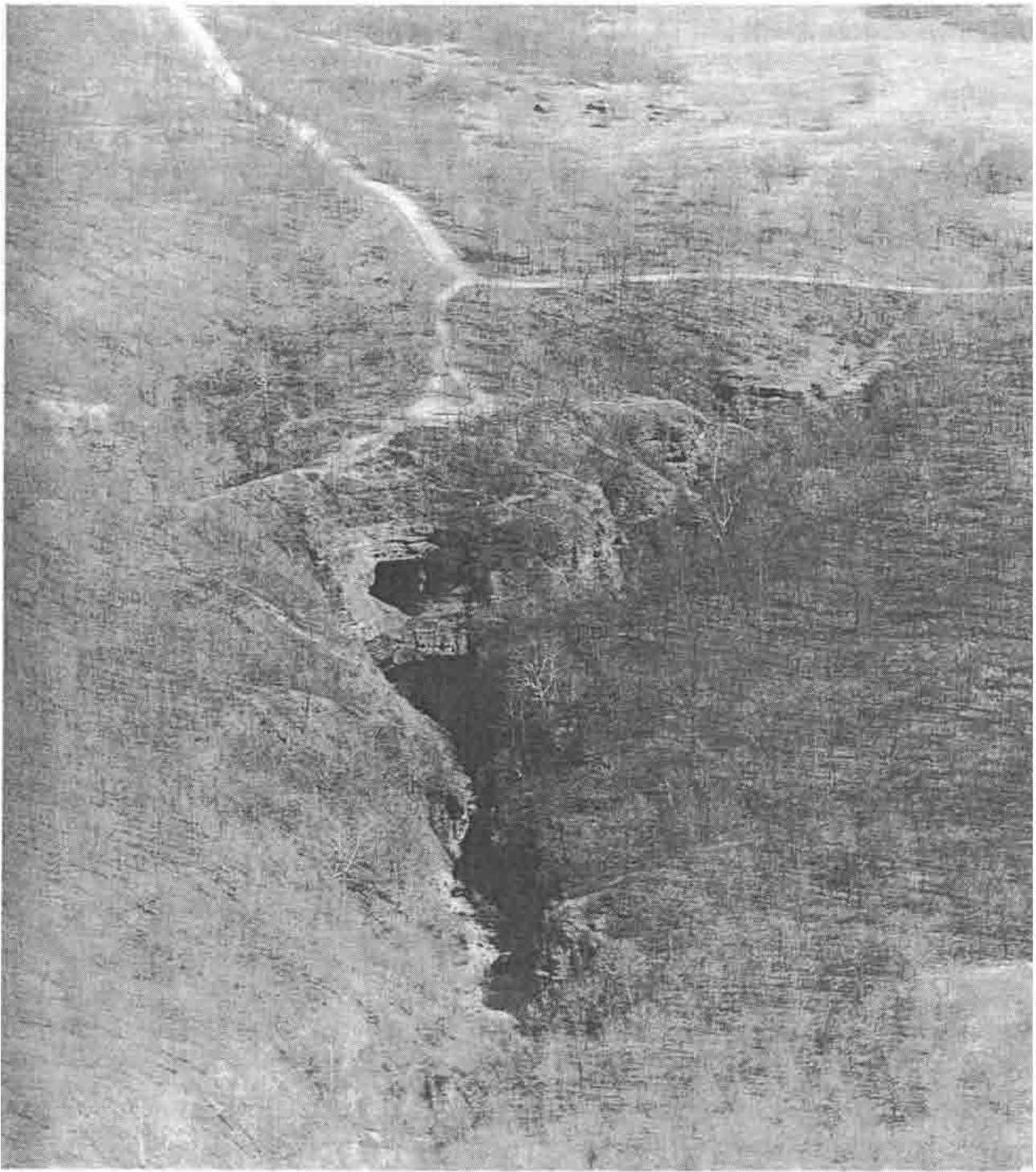


Figure 24. Grand Gulf, an immense sinkhole and collapsed cave system near Thayer in Oregon County. Photo by Jerry D. Vineyard.

Losing streams are found throughout the Salem Plateau and account for much of the rapid groundwater recharge that feeds the large spring systems. Figure 25 shows the locations of major losing-stream watersheds in

the Salem Plateau. Losing streams can be found in every county and river basin in the Salem Plateau, but are especially common in Shannon, Carter, Howell, Oregon, Texas, Phelps, Pulaski and Laclede counties. Indi-

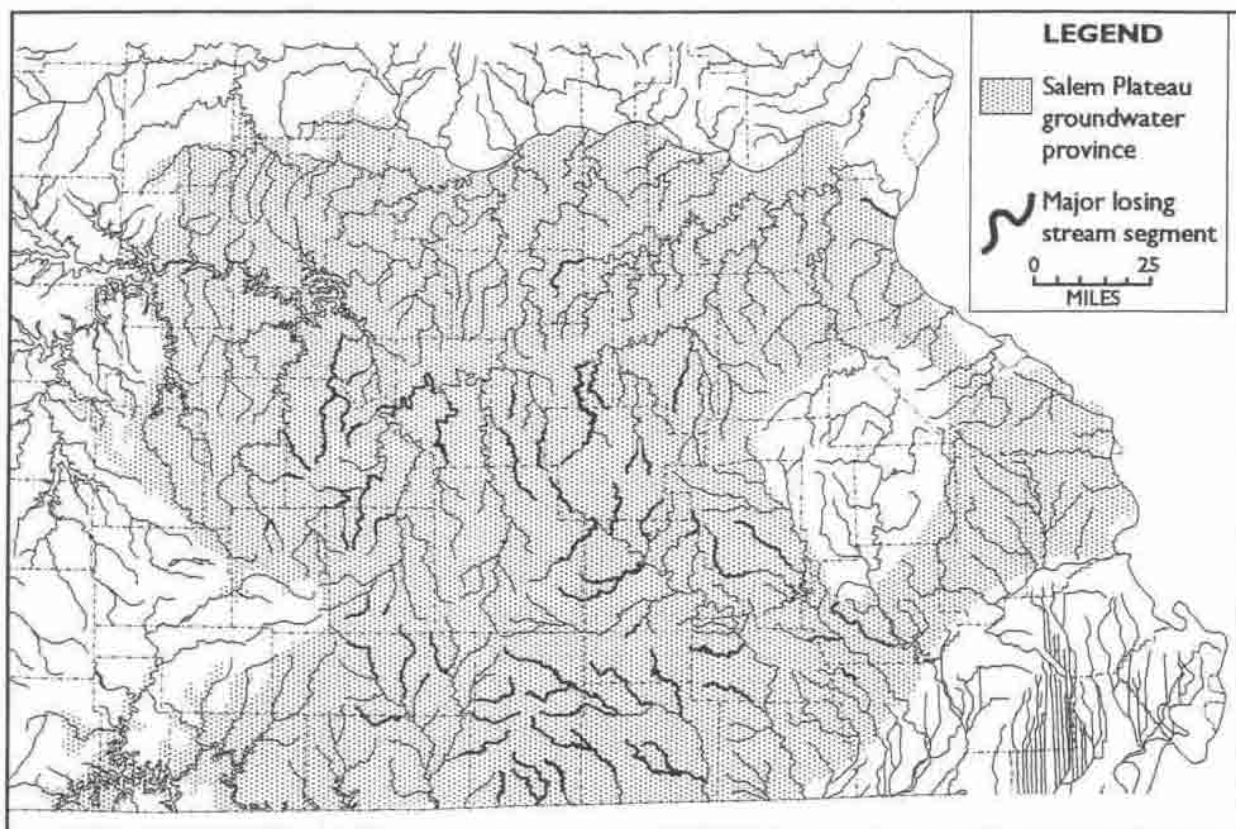


Figure 25. Major losing streams in the Salem Plateau groundwater province.

vidual losing-stream watersheds may contain more than 100 square miles of drainage where nearly all of the runoff is channeled underground rather than leaving the watershed by surface flow. In most cases, the water table in losing-stream valleys is well below streambed elevation. The presence of conduits in the subsurface that transport water to the receiving spring dewater the adjacent part of the aquifer and lowers the potentiometric surface in the vicinity of the conduits.

Caves and Karst Conduits

The Salem Plateau contains about 3,600 of Missouri's more than 5,500 known caves. Most of the caves that can be entered today in the Salem Plateau are former paths of groundwater movement that no longer transport significant volumes of groundwater. However, in some areas, particularly where sinkholes provide most of the surface drainage, enterable caves are still active groundwater con-

duits. This is especially true in parts of the eastern Salem Plateau such as Perry County. Many of the longest caves in Missouri are in Perry County, and all are active groundwater conduits that transport water from large sinkhole areas to springs and karst resurgences along area streams. Crevice, Mystery, Rimstone River caves, and the Moore Cave System in Perry County, are some of Missouri's longest caverns. Their combined mapped lengths total more than 60 miles. All of them are entered through sinkholes, drain large sinkhole plains, and discharge their waters into local gaining-stream drainages that bisect the sinkhole plains.

The springs, which are the outfalls of these cave systems, normally have small discharges. However, after heavy rainfall, these springs may discharge more than 100 ft³/sec. Normally dry karst resurgences are associated with most of these caves and springs. These karst resurgences discharge no flow except

during very wet weather when they will function briefly as overflow outlets for the karst drainage system. Any of the carbonate units in the Ozarks can host caves, but the majority of the caves are developed in the Roubidoux Formation, Gasconade Dolomite, and Eminence Dolomite. In the Perry County area, the Joachim Dolomite and Platin Limestone host many caves. The longest air-filled caves in Missouri are in Perry County and Crevice Cave, the longest, contains more than 27 miles of mapped passage.

In many types of aquifers, groundwater moves only a few feet to a few hundred feet per year. In karst areas, groundwater velocities may be several orders of magnitude greater. Groundwater velocities in karst systems in the Salem Plateau have been measured using water tracing methods. Water tracing is a

technique used to establish a physical link between where water disappears into the subsurface, such as in a sinkhole or a losing stream, to where it resurfaces at a spring or in a gaining stream segment. Water-soluble fluorescent dyes are normally used as tracing agents. Ordinarily, water tracing will not delineate the actual path that the groundwater followed. It does, however, demonstrate the physical connection between recharge and discharge points. Straight-line velocities measured using dye tracing are locally more than two miles per day. Average velocities are somewhat lower. In the central and northern parts of the province, straight-line velocities measured using tracer dyes average about 0.5 miles per day, while to the south, particularly in the Current River and Eleven Point River basins, average straight-line velocity appears

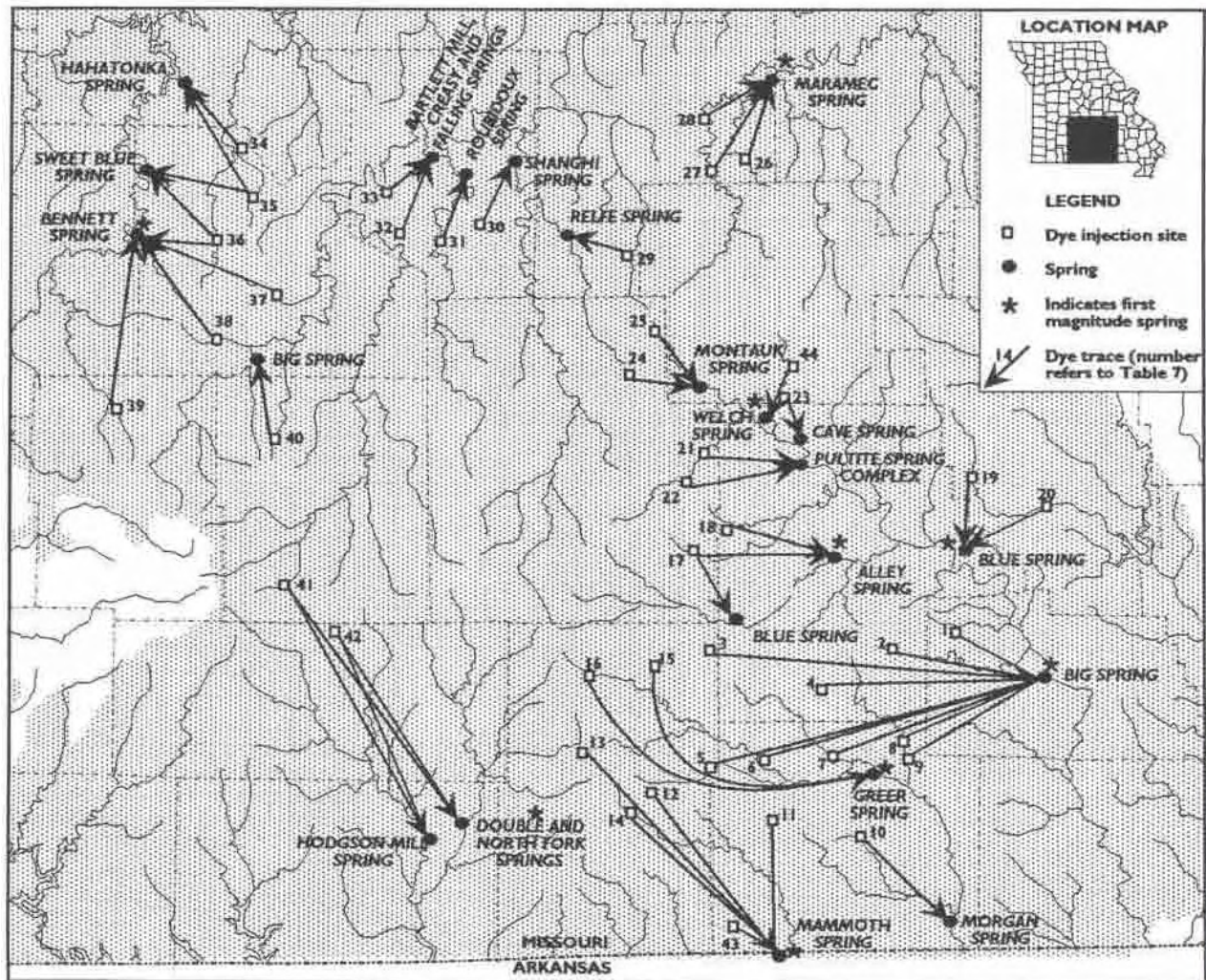


Figure 26. Selected major groundwater traces in the Salem Plateau groundwater province.

Ref. No.	Injection Data				Recovery Data				Trace Length (miles)	Data Source ***
	County	Location Sec./Twn./Rng.	Injection Date	Agent & Amount (lbs)**	Spring Name	County	Location Sec./Twn./Rng.	First Recovery Interval		
1*	Carter	4 27N 2W	8-1-84	Fl, 6	Big	Carter	6 26N 1E	8-12-95 to 8-22-95	12.4	Aley & Aley (1987)
1*	Carter	4 27N 2W	8-1-84	Fl, 6	Mill Creek	Carter	6 27N 1W	8-6-95 to 8-13-95	4.5	Aley & Aley (1987)
2	Shannon	18 27N 3W	5-10-73	Fl, 10	Big	Carter	6 26N 1E	5-16-73 to 5-22-73	19.2	Aley (1975)
3	Howell	24 27N 7W	4-17-72	Fl, 15	Big	Carter	6 26N 1E	4-25-72 to 5-2-72	38.1	Aley (1975)
4	Shannon	12 26N 5W	12-10-71	Fl, 10	Big	Carter	6 26N 1E	12-13-71 to 12-20-71	25.3	Aley (1975)
5	Howell	26 25N 7W	1-18-72	Fl, 10	Big	Carter	6 26N 1E	1-31-72 to 2-4-72	39.5	Aley (1975)
6	Oregon	14 26N 6W	8-26-71	Fl, 7	Big	Carter	6 26N 1E	10-22-71 to 11-9-71	33.5	Aley (1975)
7	Oregon	13 25N 5W	12-17-74	Fl, 8	Big	Carter	6 26N 1E	12-18-74 to 2-20-75	26.4	Aley (1975)
8	Oregon	9 25N 3W	11-18-70	Fl, 10	Big	Carter	6 26N 1E	11-24-70 to 12-1-70	17.5	Aley (1975)
9	Oregon	22 25N 3W	8-29-69	Fl, 5	Big	Carter	6 26N 1E	9-8-69 to 9-15-69	18.0	Aley (1975)
10	Oregon	28 24N 4W	5-28-69	Fl, 10	Morgan	Oregon	16 22N 2W	8-11-69 to 8-25-69	15.5	Aley (1975)
11	Oregon	29 24N 5W	12-16-70	Fl, 10	Mammoth	Fulton, AR	5 21N 5W	12-30-70 to 1-12-71	14.5	Aley (1975)
12	Howell	10 24N 8W	6-14-72	Fl, 10	Mammoth	Fulton, AR	5 21N 5W	6-22-72 to 7-5-72	25.0	Aley (1975)
13	Howell	20 25N 9W	8-14-72	Fl, 10	Mammoth	Fulton, AR	5 21N 5W	8-28-72 to 9-8-72	32.8	Aley (1975)
14	Howell	26 24N 8W	5-18-78	Fl, 10	Mammoth	Fulton, AR	5 21N 5W	5-26-78 to 5-30-78	23.4	Dean DGLS-DTDB
15	Howell	35 27N 8W	11-9-72	Fl, 15	Greer	Oregon	36 25N 4W	11-15-72 to 11-27-72	27.5	Aley (1975)
16	Howell	33 27N 9W	9-9-75	Fl, 15	Greer	Oregon	36 25N 4W	9-11-75 to 9-22-75	34.5	Tryon DGLS-DTDB
17*	Texas	22 29N 7W	4-4-78	Fl, 8	Alley	Shannon	25 29N 5W	4-5-78 to 4-19-78	14.4	Aley & Aley (1987)
17*	Texas	22 29N 7W	4-4-78	Fl, 8	Blue	Shannon	31 28N 6W	4-4-78 to 4-19-78	9.0	Aley & Aley (1987)
18	Shannon	8 29N 6W	11-1-72	Fl, 10	Alley	Shannon	25 29N 5W	11-1-72 to 11-9-72	11.0	Aley (1975)
19	Reynolds	14 30N 2W	10-7-69	Rwt, 5	Blue	Shannon	21 29N 2W	10-10-69 to 10-20-69	9.5	Feder & Barks (1972)
20	Reynolds	3 29N 1W	4-14-82	Fl, 8	Blue	Shannon	21 29N 2W	4-14-82 to 4-28-82	8.3	Aley & Aley (1982)
21*	Texas	34 31N 7W	4-2-86	Fl, 5	Pulltite Complex	Shannon	33 31N 5W	4-2-86 to 4-16-86	11.0	Aley & Aley (1987)
22*	Texas	7 30N 7W	6-16-78	Fl, 8	Pulltite Complex	Shannon	33 31N 5W	6-27-78 to 7-18-78	13.1	Aley (1978)
23	Dent	31 32N 5W	5-12-82	Fl, 8	Cave	Shannon	21 31N 5W	5-12-82 to 5-26-82	5.0	Aley & Aley(1982)
24	Texas	17 32N 8W	9-30-86	Rwt, 12	Montauk	Dent	22 32N 7W	10-13-86 to 10-21-86	8.0	Vandike/Gooding/Endicott DGLS-DTDB
25	Texas	36 33N 8W	4-8-87	Rwt, 12	Montauk	Dent	22 32N 7W	4-8-87 to 4-22-87	6.4	Vandike/Endicott DGLS-DTDB
26	Phelps	21 36N 6W	8-3-94	Fl, 6	Maramec	Phelps	1 37N 6W	8-15-97 to 8-24-94	9.6	Vandike (1996)
27	Phelps	35 36N 7W	5-13-82	Rwt, 27	Maramec	Phelps	1 37N 6W	5-25-82 to 5-26-82	12.8	Vandike (1985)
28	Phelps	26 37N 7W	3-26-94	Rwt, 9	Maramec	Phelps	1 37N 6W	4-1-94 to 4-7-94	7.8	Vandike (1996)
29	Phelps	8 34N 8W	10-4-94	Fl, 5	Relfe	Phelps	36 35N 10W	10-4-94 to 12-6-94	8.5	Vandike (1996)
30	Pulaski	32 35N 11W	6-9-71	Fl, 8	Shanghai	Pulaski	24 36N 11W	7-2-71 to 7-9-71	8.4	Tryon DGLS-DTDB
31	Pulaski	3 34N 12W	10-1-70	Fl, N/A	Roubidoux	Pulaski	25 36N 12W	N/A	10.5	DeanDGLS-DTDB
32*	Pulaski	36 35N 13W	5-5-88	Rwt, 12	Bartlett Mill	Pulaski	16 36N 12W	5-16-88 to 6-9-88	9.2	Vaughn DGLS-DTDB
32*	Pulaski	36 35N 13W	5-5-88	Rwt, 12	Creasy	Pulaski	16 36N 12W	5-15-88 to 6-4-88	9.2	Vaughn DGLS-DTDB
32*	Pulaski	36 35N 13W	5-5-88	Rwt, 12	Falling	Pulaski	17 36N 12W	5-15-88 to 6-4-88	9.0	Vaughn DGLS-DTDB

Table 7. Major groundwater traces in the Salem Plateau groundwater province.

Table 7 continued

Ref. No.	Injection Data				Recovery Data				Trace Length (miles)	Data Source ***
	County	Location Sec./Twn./Rng.	Injection Date	Agent & Amount (lbs)**	Spring Name	County	Location Sec./Twn./Rng	First Recovery Interval		
32*	Pulaski	36 35N 13W	5-5-88	Rwt, 12	Sowers	Pulaski	16 36N 12W	5-15-88 to 6-4-88	9.2	Vaughn DGLS-DTDB
33*	Pulaski	10 35N 13W	3-19-92	Rwt, 9	Bartlett Mill	Pulaski	16 36N 12W	3-26-92 to 4-2-92	7.1	Vandike DGLS-DTDB
33*	Pulaski	10 35N 13W	3-19-92	Rwt, 9	Creasy	Pulaski	16 36N 12W	3-26-92 to 4-2-92	6.6	Vandike DGLS-DTDB
33*	Pulaski	10 35N 13W	3-19-92	Rwt, 9	Falling	Pulaski	17 36N 12W	3-26-92 to 4-2-92	6.5	Vandike DGLS-DTDB
34	Laclede	24 36N 16W	4-18-80	Rwt, 35	Hahatonka	Camden	2 37N 17W	4-25-80 to 5-2-80	11.0	Miller/Vandike DGLS-DTDB
35*	Laclede	30 35N 15W	11-3-76	Rwt., N/A	Sweet Blue	Laclede	30 36N 17W	11-26-76 to 12-5-76	13.4	Miller/Skelton DGLS-DTDB
35*	Laclede	30 35N 15W	11-3-76	Rwt, N/A	Hahatonka	Camden	2 37N 17W	12-18-76 to 12-26-76	17.6	Miller/Skelton DGLS DTDB
36*	Laclede	4 34N 16W	4-19-90	Fl, 6	Bennett	Dallas	1 34N 18W	5-3-90 to 5-14-90	9.1	Vandike 1992
36*	Laclede	4 34N 16W	4-19-90	Fl, 6	Sweet Blue	Laclede	30 36N 17W	5-3-90 to 5-14-90	11.7	Vandike (1992)
37	Laclede	28 34N 15W	2-27-90	Rwt, 12	Bennett	Dallas	1 34N 18W	3-22-90 to 3-27-90	16.2	Vandike (1992)
38	Laclede	28 33N 16W	7-26-90	Fl, 5	Bennett	Dallas	1 34N 18W	8-6-90 to 8-7-90	14.7	Vandike (1992)
39	Webster	3 31N 18W	11-21-89	Rwt, 12	Bennett	Dallas	1 34N 18W	12-5-89 to 12-18-89	19.3	Vandike (1992)
40	Wright	28 31N 15W	1-11-90	Fl, 15	Big	Laclede	6 32N 15W	1-11-90 to 2-21-90	10.3	Vandike (1992)
41*	Wright	11 28N 15W	4-18-86	Fl, 10	Double	Ozark	32 24N 11W	4-18-86 to 5-2-86	34.8	Williams DGLS-DTDB
41*	Wright	11 28N 15W	4-18-86	Fl, 10	North Fork	Ozark	28 24N 11W	4-18-86 to 5-2-86	34.5	Williams DGLS-DTDB
41*	Wright	11 28N 15W	4-18-86	Fl, 10	Hodgson Mill	Ozark	34 24N 12W	4-18-86 to 5-2-86	33.2	Williams DGLS-DTDB
42*	Douglas	3 27N 14W	11-2-88	Rwt, 12	Double	Ozark	32 24N 11W	11-10-88 to 11-17-88	27.7	Pendleton/Brown DGLS-DTDB
42*	Douglas	3 27N 14W	11-2-88	Rwt, 12	North Fork	Ozark	28 24N 11W	11-10-88 to 11-17-88	27.5	Pendleton/Brown DGLS-DTDB
42*	Douglas	3 27N 14W	11-2-88	Rwt, 12	Hodgson Mill	Ozark	34 24N 12W	11-10-88 to 11-17-88	26.4	Pendleton/Brown DGLS-DTDB
43	Oregon	20 22N 6W	10-16-67	Fl, 0.5	Mammoth	Fulton, AR	5 21N 5W	10-16-67 to 10-17-67	7.0	Aid DGLS-DTDB
44	Dent	8 32N 5W	12-4-85	Fl, 6	Welch		10 31N 6W	12-7-85 to 12-22-85	7.1	Aley & Aley (1987)

* Dye recovered at multiple springs

** Fl - Fluoroscein or Uramine C; Rwt - Rhodamine WT

*** DGLS-DTDB - Division of Geology and Land Survey Dye Trace Database

to be closer to 1 mile per day. Velocities are generally highest following heavy precipitation and lowest during extended periods of dry weather. Dye traces greater than 35 miles in length have been conducted in the Salem Plateau in some of the larger spring systems. Figure 26 is a map of the Salem Plateau groundwater province showing the injection points and resurgence points for major water or dye-tracing studies. Table 7 lists physical data for these dye traces.

Springs

Springs are the primary outlet points for groundwater moving through karst groundwater systems, and the Salem Plateau is host to thousands of springs. There are more than 2,900 springs recorded in Missouri, with an estimated 1,500 of these in the Salem Plateau. There very likely exists a great number of smaller springs for which no information has been gathered.

Springs in the Salem Plateau range from spectacular groundwater outlets such as Big Spring and Greer Spring, with flows averaging several hundred million gallons a day, to very small springs with discharges of only a few gallons a minute. Springs are commonly classified by their size. One technique for classifying springs is by the magnitude of their discharge. Meinzer (1927) devised a spring discharge classification system that is still widely used. The system, shown in table 8, divides springs into five magnitudes. The larger the spring, the smaller the magnitude number.

MAGNITUDE	DISCHARGE
First	100 ft ³ /sec or greater
Second	10 to 100 ft ³ /sec
Third	1 to 10 ft ³ /sec
Fourth	100 gpm to 1 ft ³ /sec (448.8 gpm)
Fifth	10 to 100 gpm

Table 8. Meinzer's (1927) classification system for springs.

Under Meinzer's classification, a first magnitude spring has an average flow in excess of 100 ft³/sec or 64.6 million gallons a day.

Missouri has eight known first magnitude springs. All of them are in the Salem Plateau groundwater province, and all of them discharge from deep water-filled cave openings developed in the lower Gasconade and Eminence dolomites. The largest is located in Carter County south of Van Buren near the Current River, and is appropriately named "Big Spring." There are easily a dozen springs in Missouri named Big Spring, and local standards obviously apply when giving springs their name. The smallest "Big Spring" is but a trickle when compared to Big Spring in Carter County, which has an average discharge of 446 ft³/sec, or 288 million gallons per day, and is one of the worlds largest single-outlet springs (Vineyard and Feder, 1982). Twenty three miles southwest of Big Spring near the Eleven Point River in Oregon County is Missouri's second largest spring, Greer Spring. Greer Spring discharges from two outlets spaced a few hundred feet apart in the base of a steep valley. It has an average discharge of 388 ft³/sec (251 million gallons per day). Table 9 shows the names and locations of Missouri's eight largest springs.

Springs show tremendous variation in appearance, discharge, flow characteristics, and water quality. However, all springs have one common characteristic—each has an area from which it receives recharge. Most commonly, a spring's recharge area supplies water to only that spring, but there are many cases where two or more springs share a common recharge area. The size of area needed for recharging a spring depends on the recharge rate and the discharge of the spring. The source of the recharge is ultimately precipitation. However, only a part of the total precipitation is available for groundwater recharge; most of the water is lost back to the atmosphere through evaporation or transpired by plants. These two losses account for about two thirds of the available water. Of the remaining one-third, some may be lost from the recharge area by surface flow. Realistically, a maximum of about 12 inches of water per year is available for groundwater recharge in most areas of the Salem Plateau, in many cases the amount may be substantially less.

Spring	LOCATION				DISCHARGE (ft ³ /sec)			
	County	Sec.	Twn.	Rng.	min.	max.	avg.	number of measurements
Big	Carter	6	26N	1E	236	2000*	447	Continuous, 1921-96
Greer	Oregon	36	25N	4W	104	1010	344	Continuous, 1921-96
Welsh	Shannon	14	31N	6W	70	492	186	38 measurements—1923-94
Bennett	Dallas	1	34N	18W	55	6350**	177	Continuous, 1916-20, 1928-41, 1965-93
Maramec	Phelps	1	37N	6W	56	1100	155	Continuous, 1903-05, 1922-29, 1965-85
Alley	Shannon	25	29N	5W	54	2750	135	Continuous, 1928-39, 1965-79
Blue	Shannon	21	29N	2W	62	301	131	47 measurements—1923-94
Double	Ozark	32	24N	11W	47	232	127	27 measurements—1919-66

* = estimated
** = flow includes runoff from Spring Hollow

Table 9. Names, locations and discharge characteristics of first magnitude springs in Missouri.

In general, the larger a spring's discharge, the larger the recharge area. A spring discharging an average flow of 10 gpm most likely has a recharge area that is relatively small, and close to the spring. Assuming an average recharge rate of 12 inches per year, a spring with a discharge averaging 10 gpm would need a recharge area of only about 16 acres. A spring with an average flow of 100 ft³/sec would require a much larger recharge area, 113 square miles, assuming a recharge rate of 12 inches per year. Thus, assuming a recharge rate of 12 inches per year, Big Spring would require a recharge area of about 505 square miles. Obviously, if two springs have similar recharge rates, the spring having the lower average discharge would require proportionally less recharge area. The recharge area size of a spring can be calculated from spring discharge and recharge rates using the following equation:

$$RA = 13.584 \times Q_{avg} / R$$

where: RA = recharge area (mi²)

Q_{avg} = average discharge (ft³/sec)

R = average annual recharge (inches)

The recharge areas for many springs in the Salem Plateau have been at least partly delineated using water tracing techniques. However, even where extensive water tracing studies have been conducted, it is not possible to delineate a spring recharge area with total

accuracy. It is simply not feasible to conduct dye traces from all possible recharge sources. Despite this, much is known about the recharge areas and flow characteristics of many springs in the Salem Plateau. Though it is beyond the scope of this report to present detailed discussions of numerous springs, some examples of the springs and their flow characteristics are necessary to show the complexity of these karst drainage systems.

Aside from being the largest single-outlet spring in Missouri, Big Spring has some very interesting hydrologic characteristics. Big Spring discharges from the Eminence Dolomite at the base of a steep bluff only a few hundred feet from the banks of the Current River a few miles south of Van Buren in Carter County. Although the spring is within the Current River basin, most of its recharge originates from outside of the Current River basin. Numerous dye traces by Aley (1975, 1987), Duley (1982) and others show that Big Spring receives more recharge from water lost into the subsurface within the Eleven Point River basin than from within the Current River basin. The upper Eleven Point River contains numerous losing-stream reaches, and most of its northern tributaries are also losing-stream watersheds. Much of this water is pirated from the Eleven Point River basin and channeled through the subsurface into the Current River basin to recharge Big Spring.

The interbasin transfer of groundwater from the Eleven Point River into the Current River through Big Spring results in an increase in average annual runoff for the Current River and a decrease in runoff for the Eleven Point River. This can easily be seen by comparing runoff rates for the two rivers. The Current River basin upstream from Van Buren, which is about three miles upstream from Big Spring, has an average annual runoff rate of 16.23 inches. In other words, the volume of water flowing by Van Buren during an average year would cover the entire Current River basin upstream of it to a depth of 16.23 inches. The addition of water from Big Spring and other smaller springs downstream of Van Buren raises the average annual runoff rate to 18.70 inches, which is observed at the USGS gaging station at Doniphan, a few miles downstream from Big Spring. The long-term average runoff rate for the Eleven Point River upstream of the

U.S. 160 bridge near Bardley is more than 5 inches lower at 13.45 inches. The difference between the two is mostly the water that is pirated from the Eleven Point and channeled into the Current.

Big Spring, like nearly all major springs in the Salem Plateau, responds quickly to precipitation in the recharge area. The recharge changes more than just the discharge of Big Spring—it also raises the water level in the aquifer. The Division of Geology and Land Survey has maintained a groundwater-level observation well about one-half mile west of Big Spring since 1971. The water level in the well, which is 56 ft deep and produces from the Eminence Dolomite, fluctuates with precipitation in much the same way as Big Spring discharges (figure 27). So close is the relationship between water level in the observation well and the discharge of Big Spring that the spring's discharge can be closely estimated from water level in the well.

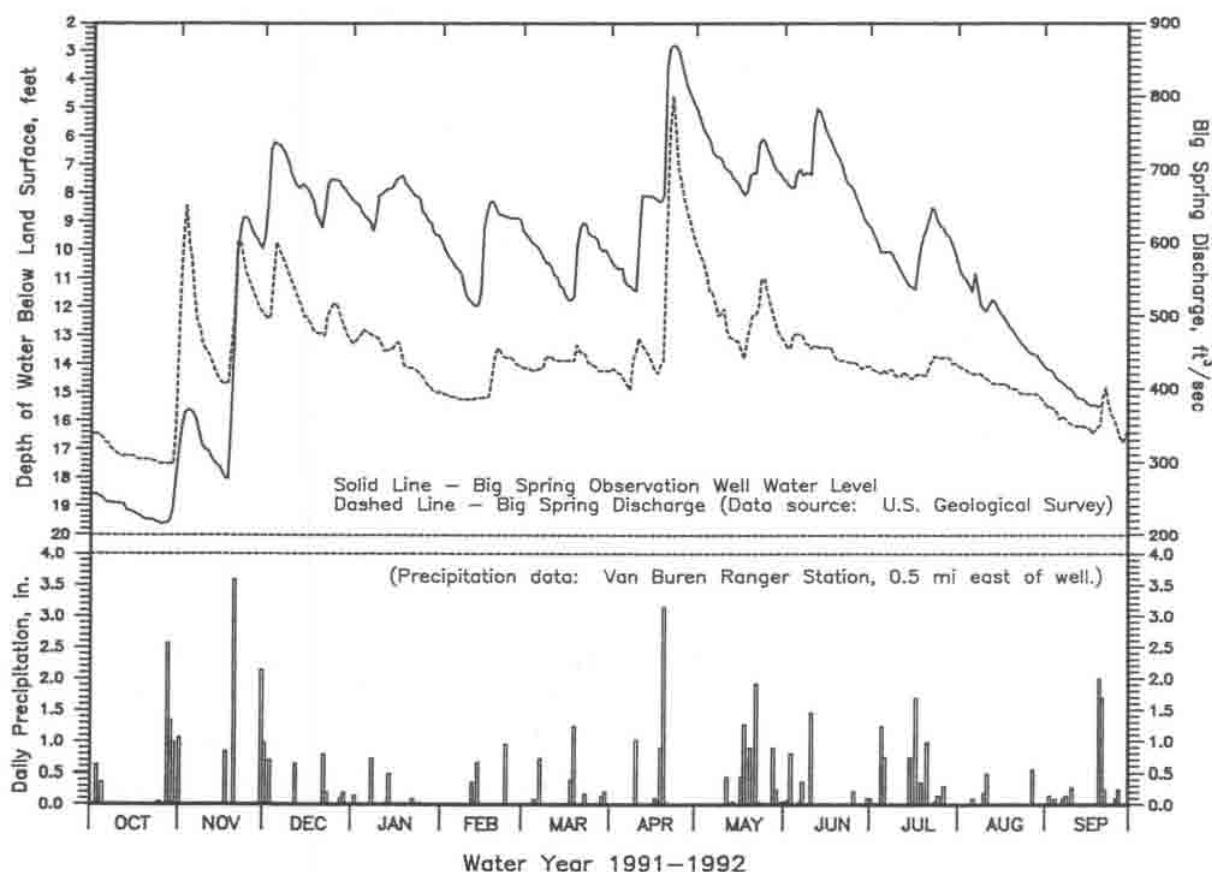


Figure 27. Groundwater-level hydrograph of Big Spring observation well, discharge of Big Spring, and local precipitation.

Big Spring is not the only spring in the Current River basin that receives recharge from outside of the basin boundaries. Blue Spring in Shannon County near Owls Bend has an average discharge of about 131 ft³/sec and is Missouri's seventh largest spring. Water tracing by Feder and Barks (1972) and Aley and Aley (1982) show that much of the water that discharges from Blue Spring originates within the Black River basin. Logan Creek, a large Black River tributary, contains gaining-stream reaches at either end of the watershed, but has a losing reach several miles long through the middle of the watershed. Upstream of the losing reach, Logan Creek drains an area of about 82 square miles. Dye introduced into Logan Creek where flow ends at the upper end of the losing reach reappears at Blue Spring nearly nine miles to the southwest.

Blue Spring has the distinction of being Missouri's deepest known spring. Like nearly all of the first magnitude springs, the submerged cave that channels water to the mouth of Blue Spring is steeply inclined for the first few hundred feet and then assumes a more horizontal nature. Divers working in Blue Spring report reaching depths of nearly 300 ft before the water-filled cave becomes nearly horizontal. Most of the other first magnitude springs that have been explored by divers are about 100 to 140 ft deep.

Many Missouri spring systems are quite complex. The simplest case is a single spring that is recharged from a particular area that supplies water to only that spring. More complex systems have several springs that share parts or all of their recharge area. Double Spring in Ozark County is the largest spring in the North Fork River basin and, with an average discharge of about 127 ft³/sec, is about the eighth largest in Missouri. A short distance upstream from Double Spring, North Fork Spring rises from the bed and banks of the North Fork River and adds an average of about 70 ft³/sec into the river. The hydrologic connection between these two springs was determined by dye tracing in the 1970s, but additional study several years later showed that Double and North Fork springs are also hydro-

logically connected with Hodgson Mill Spring, which is about 5 miles west of them in the Bryant Creek basin. Williams (1987) conducted several water traces from the headwaters of the Gasconade River basin near Mansfield. Dye from all of these traces was recovered at Double, North Fork and Hodgson Mill springs. Water samples collected periodically from all three springs during a several year period shows that the water discharging from them is essentially identical, even its chemistry. This strongly indicates that the springs are separate outlets for a single karst drainage system, and share a common recharge area.

One of the most interesting characteristics of springs is how they respond to precipitation. The discharge rate of many springs rises dramatically shortly after a rainfall event. The discharge decreases nearly as rapidly for a short time after the discharge peaks, but then the recession curve flattens as the discharge approaches the pre-storm discharge value (figure 28). This is explained when one considers that a spring is nothing more than the discharge point for a complicated three-dimensional underground drainage system. Intersecting fractures within the recharge area for the spring transport water through progressively larger cracks and crevices toward the spring.

Maramec Spring, near St. James in Phelps County, is Missouri's 5th largest with an average discharge of about 155 ft³/sec. It receives recharge from several losing-stream watersheds in the upper Meramec River basin including Dry Fork, Norman Creek, Asher Hollow, and several of their tributaries. Several detailed studies of Maramec Spring allowed the collection of extensive discharge, precipitation, and water quality information. In one study, water samples were collected from the spring at 4-hour intervals for a one-year period (Driess, 1989).

In another study, a specific conductance probe and data logger were installed in the spring branch that collected hourly specific conductivity values for more than a year. Specific conductivity is a measure of the electrical conductance of water. The conductivity

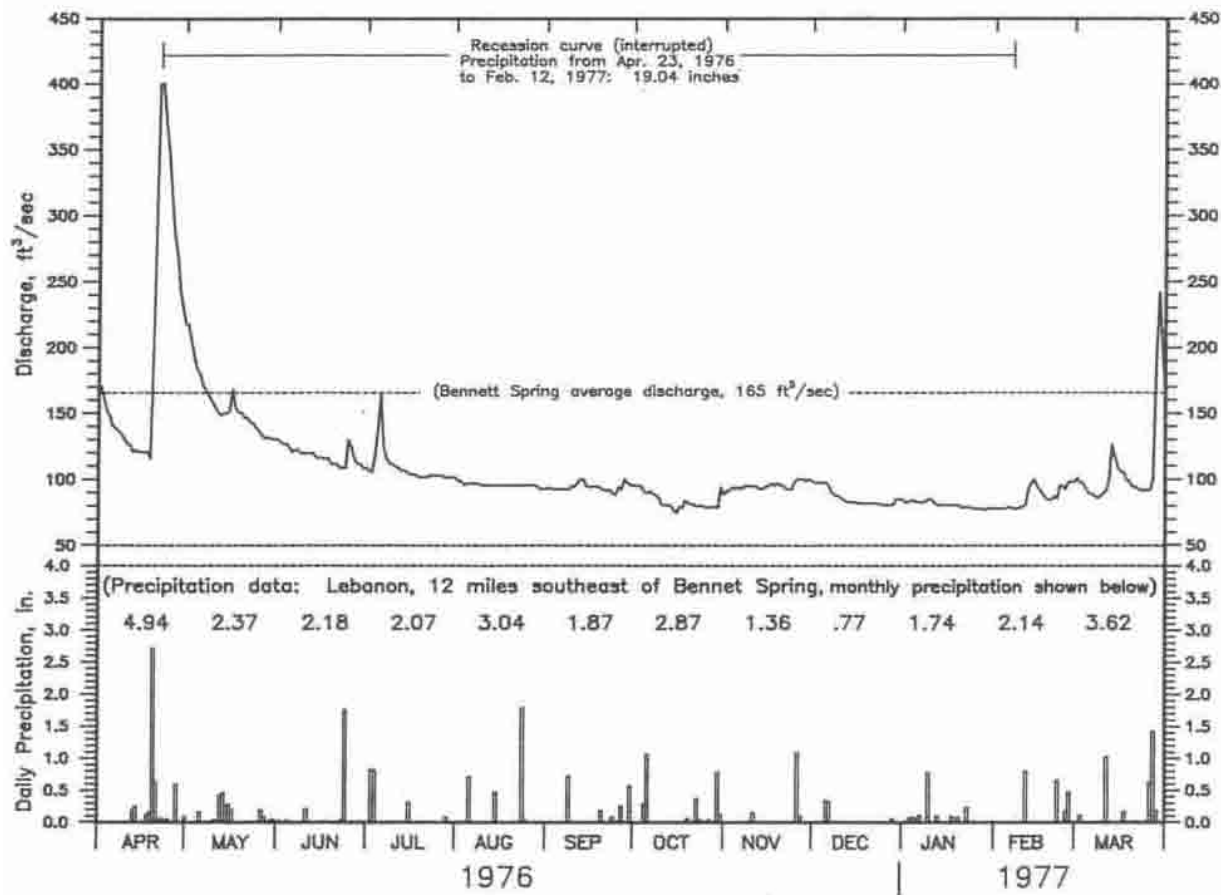


Figure 28. Recession hydrograph, Bennett Spring, Laclede County.

of water is directly proportional to the quantity of dissolved minerals. Precipitation, before reaching the ground, contains very little dissolved minerals and thus has a very low conductivity. Once in contact with the earth materials, the water begins dissolving rock and increasing its dissolved solids load. In a spring system, recent recharge generally has a significantly lower conductivity than water which has been in the spring system and in contact with the rock for a longer period. There are several National Weather Service precipitation stations in the area, some of which collect hourly rainfall data. Additional precipitation stations were established in the recharge area during both studies to allow hourly rainfall amounts to be measured and recorded.

Discharge data is collected at Maramec Spring through a digital water-level recorder

that takes hourly spring-stage readings. The stage values are converted to discharge values through a stage-discharge rating table developed for the spring.

The detailed water quality, discharge and precipitation data collected from Maramec Spring and its recharge area shows that discharge begins increasing at the spring within a few hours of when rainfall begins. Discharge peaks soon after rainfall ceases, and then begins decreasing. Water from the rainfall event however, does not reach Maramec Spring for several days. The increase in discharge is due to an increase in head pressure in the recharge area from the influx of recharge. The recharge causes the water level in the aquifer to rise, which forces the water already in the conduit system to increase in velocity. The process is much the same as having a long garden hose attached to a faucet

that is partially opened. If the faucet is then fully opened, flow begins increasing immediately at the end of the hose, but the water that caused the flow to increase does not reach the nozzle for some time. At Maramec Spring, most of the recharge from a precipitation event reaches the spring several days after the discharge peak occurs. As the fresh recharge begins exiting from the spring, the dissolved solids load of the water begins decreasing, as does the specific conductance. This is because the water has not been in contact with the earth materials long enough to have an appreciable amount of materials. As the fresh recharge drains through the system, it will slowly increase its dissolved solids content, and a few weeks after the rainfall event the chemistry of the water approximates the pre-storm conditions (figure 29).

During dry weather, discharge at Maramec Spring slowly decreases as water-level

in the aquifer in the recharge area declines. During very dry weather, nearly all of the spring discharge is derived from aquifer storage. This is water that has been in contact with the rock for a longer period of time, and subsequently the dissolved solids content of the water is relatively high (Vandike, 1996).

The discharge characteristics of springs also give important clues to the size of the recharge area and the storage characteristics of the karst aquifer. Most springs have maximum discharges that are 5 to 10 times greater than their average discharges. A few springs have relatively steady discharges and show little response to local precipitation. These springs may have a relatively large recharge area, but the bedrock openings are likely small and cannot accept or transmit large quantities of water after major precipitation events. These springs are referred to as high-storage springs. At the opposite end of the spring spectrum are

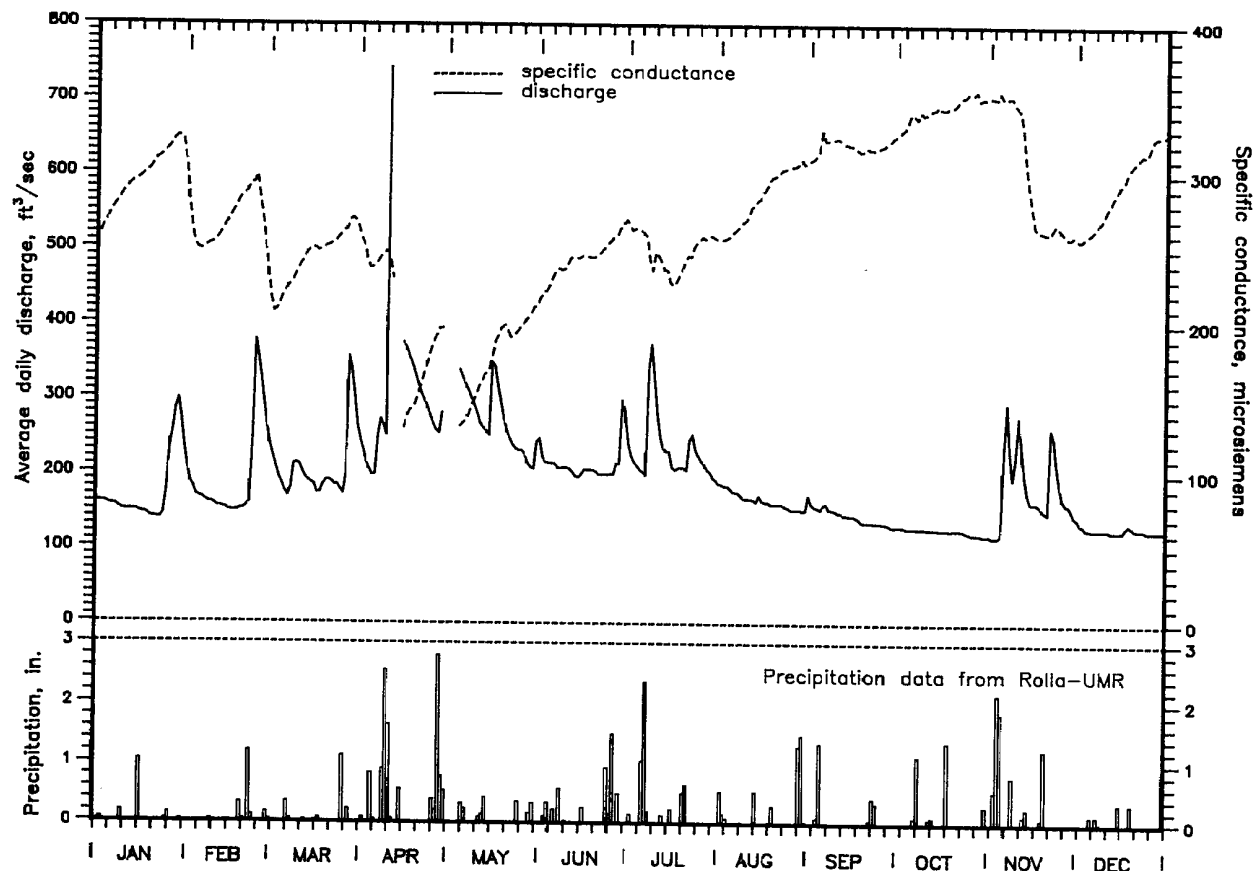


Figure 29. Discharge and specific conductance at Maramec Spring, and precipitation at University of Missouri—Rolla (from Vandike, 1996).

the high-transit springs that have little or no discharge during dry weather, but discharge large quantities of water briefly after heavy precipitation. High-transit springs are common in the Perryville area where extensive cave systems transport water from sinkhole plains to springs and karst resurgences. The karst resurgences are essentially overflow outlets. They are normally dry, functioning only after heavy rainfall. Some may discharge more than 100 ft³/sec for a few hours after heavy rainfall, and a day later be completely dry.

A feature common in the southeastern Missouri area is the presence of thick residuum. Residuum is unconsolidated clay, silt and rock fragments that form from the weathering of the bedrock formations. Normally less than 20 feet thick in most of the Salem Plateau, residuum can exceed 200 feet in thickness in much of southeastern Missouri. Residuum is generally very permeable, and allows rapid downward movement of recharge. In essence, the residuum often acts as a storage medium; recharge water is stored in openings in the residuum after heavy precipitation and later released to bedrock aquifers.

GROUNDWATER CONTAMINATION POTENTIAL

The contamination potential at any location in the Salem Plateau groundwater province largely depends on the vertical hydraulic conductivity of the formations at or near land surface. Pennsylvanian-age bedrock overlies the Ozark aquifer in a small area of the north-central part of the province and provides fairly adequate protection from contamination sources. The siltstone, shale, and low permeability limestone and sandstone layers act as natural barriers in preventing downward movement of contaminants.

Jefferson City-Cotter dolomites, and the upper Gasconade Dolomite tend to be dense, and only moderately permeable. Though generally fractured, the fractures are typically not well interconnected and appreciably enlarged by the dissolution of the carbonate rock. Contaminants entering these formations tend to move slowly. However, due to the

relatively low permeability and slower rate of recharge in these formations, contaminants introduced into them are also flushed slowly from them.

Where at or near land surface, highly permeable formations such as the Roubidoux Formation, the lower Gasconade Dolomite (including the Gunter Sandstone Member), and the Potosi Dolomite can easily become contaminated due to surface activities. With rare exception, these formations pose significant limitations on the development of most types of waste-disposal systems. Since these units also commonly host losing streams, sinkholes and other karst features, contaminants introduced into groundwater in discrete recharge settings can affect groundwater quality at springs a considerable distance away. Although groundwater in these settings can easily be contaminated, once the source of contamination is removed or the contaminants treated, water quality normally recovers quickly. For example, a November 1981 pipeline leak in a losing-stream watershed in southern Phelps County caused serious water-quality problems at Maramec Spring 12 miles northeast of the spill site. An estimated 24,000 gallons of liquid fertilizer containing ammonium nitrate and urea entered the subsurface in a losing reach of Dry Fork where the channel is developed in the lower Gasconade Dolomite. Although a large quantity of liquid fertilizer was spilled, it moved quickly through solution-enlarged bedrock openings, and within a few weeks was no longer detectable at the spring. It is interesting to note that although this spill severely affected water quality at Maramec Spring for several weeks, none of the several hundred private domestic wells in the area between the spill site and Maramec Spring were found to be affected (Vandike, 1982).

Contaminants entering conduit systems supplying major springs tend to follow very localized, well-defined flow paths. Had this spill occurred in a diffuse recharge upland setting, Maramec Spring would likely not have been severely affected because the contaminants would have reached the spring over a far

longer period of time. Instead of affecting groundwater quality for only a few months, a major spill in a diffuse recharge setting may have affected groundwater quality for months or even years.

Ordovician-age dolomites and sandstones form the bedrock surface over most of the Salem Plateau groundwater province, and are tapped by most of the thousands of domestic and farm wells in the region. Statistically, it is these wells that are most often affected by surface activities and poor waste disposal practices. This is due in part to how private wells are constructed. Prior to passage of the Water Well Drillers Act (RSMo 256.600-256.640) in 1985, there were no laws, rules or regulations governing the drilling of water wells or the construction of private wells; however, the construction of public water supply wells has been regulated in Missouri for many years. Private wells, especially those constructed prior to 1987, when water well drilling regulations became effective, are constructed to much less stringent standards than public water supply wells. Most older private

wells contain less than 80 feet of casing that is not effectively sealed to preclude contaminants from entering the well from around the outside of the casing. Another reason that private wells are more likely to become contaminated is that they typically produce from relatively shallow aquifer zones. In a setting such as the Salem Plateau, shallow aquifer zones are much more likely to be affected by surface activities than deeper aquifer zones.

The deeper Cambrian-age formations provide much of the population of the area with water through municipal or public water-supply wells. These wells are cased much deeper than private wells; their casings are sealed full length with cement grout, and the aquifer zones they produce from are not at or near land surface over most of the province. Still, reasonable caution is necessary to prevent contamination of these units. Any prospective disposal site, such as a landfill or lagoon, should have a thorough geological evaluation to determine the probable effects on groundwater quality.

THE SPRINGFIELD PLATEAU GROUNDWATER PROVINCE

INTRODUCTION

The Springfield Plateau groundwater province in Missouri covers all or parts of 27 counties in the southwestern and west-central part of the state, and includes an area of about 8,900 square miles. It is bounded on the east by the Eureka Springs escarpment, to the northwest by the freshwater-salinewater transition zone, and to the south and southwest by parts of Arkansas, Oklahoma, and Kansas. Thick dolomites and sandstones comprising the St. Francois, Ozark, and Springfield Plateau aquifers underlie the region. In terms of importance for groundwater supplies and volume of fresh water in storage in consolidated-rock aquifers, this province ranks second in importance as a groundwater resource base.

Exposed bedrock units in this province range in age from Lower Ordovician through Pennsylvanian, but Mississippian-age limestone units form the bedrock surface in about 90 percent of the province (table 10). Most of the Cambrian and Ordovician formations that underlie the Salem Plateau are present in the subsurface in the Springfield Plateau, but may not crop out at the surface.

GEOLOGY

The main geologic difference between the Springfield Plateau groundwater province and the Salem Plateau groundwater province is the presence of a thick sequence of Mississippian-age rocks that overlie older Ordovician strata in southwestern Missouri. The Mississippian rocks, being primarily lime-

stones, weather somewhat differently than dolomites, and present a different type of karst development than what is seen in the Salem Plateau. Karst development is at least as common here as in the Salem Plateau, but individual karst drainage systems are not as widespread. There are no first magnitude springs in the Springfield Plateau groundwater province, and relatively few second magnitude springs. Caves are common in many of the counties, and many are still active groundwater conduits. A higher proportion of the caves in the Springfield Plateau are entered from sinkholes than in the Salem Plateau.

In many ways, the Springfield Plateau landscape appears to be younger than that of the Salem Plateau. Karst development has had a profound impact on the formation of surface features, but the solutional activity, which produces karst features, probably started much later here than in the Salem Plateau. The Mississippian-age strata in southwestern Missouri were overlain by relatively impermeable Pennsylvanian-age sedimentary deposits for a longer period than the Ordovician-age rocks in the Salem Plateau were covered by younger sediments. There are limited parts of the Salem Plateau groundwater province that were capped by relatively impermeable bedrock that helped prevent extensive bedrock weathering. In general, though, surface weathering has apparently been in progress longer in the Salem Plateau than in the Springfield Plateau. As a result, the subsurface conduit systems in the Springfield Plateau typically

System	Series	Group or Formation	Thickness (In Feet)	Lithology	Hydrology	Remarks
Pennsylvanian		Undiff. Penn. Strata	1-120	Siltstone, sandstone, shale and thin limestone.	Not a significant aquifer	Western Interior Confining Unit
Mississippian	Meramecian	Warsaw Fm. and younger Mississippian Strata	200 (?)	Alternating limestone and shale formations.	Not a significant aquifer	Springfield Plateau Aquifer
	Osagean	Burlington-Keokuk Limestone	100-200	White to gray, medium- to coarse-crystalline, medium- to thick-bedded limestone. Relatively young karst features.	Small to moderate yields (10-30gpm) in Springfield Plateau province. Locally, where more deeply buried in western part of province, may yield as much as 100 gpm.	
		Elsey Formation	Average-30	Similar to Reeds Spring Fm., but chert is white and is mottled with round spots.		
		Reeds Spring Formation	0-100	Alternating beds of finely-crystalline limestone, and sandy chert. Unit is about 50% chert.		
		Pierson Limestone	5-55	Medium- to massively-bedded limestone, cherty limestone.		
	Kinderhookian	Northview Formation	2-80	Lower part is greenish gray shale, upper part is siltstone.	Acts as aquiclude to separate Springfield Plateau Aquifer from Ozark Aquifer.	Ozark Confining Unit
		Sedalia Formation	0-50	Similar to Compton Formation, but more thickly-bedded. Interfingers with Compton.	Not water bearing	
		Compton Formation	5-30	Finely-crystalline, crinoidal limestone. Thin-bedded with greenish shale beds.		
Devonian	Late	Chattanooga Shale	0-30	Fissile, black, carbonaceous, sandy shale. Has oily or bituminous odor.	Could cause water quality problems if left uncased in wells. Contained water is high in sulfates and may have H2S gas.	
Ordovician	Canadian (lower)	"Powell" Dolomite	0-80	Fine- to medium-crystalline dolomite.	Not considered to be important aquifers. May yield 10 to 20 gpm locally to private, domestic wells.	Ozark Aquifer
		Cotter Formation	175-400	Lithology similar to Ozark Province.		
		Jefferson City Formation	Average-210	Silty dolomite, bedded oolitic chert.		
		Roubidoux Formation	140-210	Less sandstone than Ozark Province (only 10%). Primarily a cherty dolomite.	Yields 60-200 gpm	
		upper Gasconade Dolomite	40-70	Chert-free, medium-crystalline dolomite.	Probably yields 30 to 100 gpm in the province.	
		lower Gasconade Dolomite	240-335	Cherty dolomite, may contain 60% chert.		
		Gunter Ss. Member	Average-30	Sandy dolomite-30% to 50% sand.	Yields 25 to 150 gpm	
Cambrian	Croixian	Eminence Dolomite	0-340	Lithology becomes like Potosi Dolomite from east to west across province.	Yields 50 to 150 gpm	
		Potosi Dolomite	0-50	Lithology unchanged from Ozark Province. Interfingers with Eminence Dolomite.	Yields as high as 1,200 gpm. Range in yield 400-1,200 gpm, average 600 gpm.	
		Derby-Doerun Dolomite	0-50	Thins to the west, may be absent at the state line. Similar to Ozark Province.	Yields 30-50 gpm locally	
		Davis Formation	0-100	Similar to Ozark Province, but less shale, more limestone to the west.	May yield 10-30 gpm in western part of province. Locally a confining unit.	St. Francois Confining Unit
		Bonneterre Dolomite	0-380	Thins to the west, may be absent at state line.	Yields are probably 10-20 gpm.	St. Francois Aquifer
		Lamotte-Reagan Sandstone	0-350 Average 200	Similar to Ozark Province, less arkose in lower part. Transgressive to west.	Yields 100-200 gpm	
Precambrian				Igneous & Metamorphic rocks	Not an aquifer	Basement Confining Unit

Table 10. Stratigraphic section of the Springfield Plateau groundwater province.

drain smaller areas than those in the Salem Plateau, and the thickness of residual material produced by weathering is less.

Structural features such as faults, folds, and fractures are much more apparent in the Springfield Plateau groundwater province than in the Salem Plateau groundwater province. Although it is recognized that the Salem Pla-

teau has undergone intense structural deformation, deep weathering has developed thick mantles of residual materials that obscure the surface view of many structural features. This deep weathering is absent in the Springfield Plateau, and here it is much easier to see geologic structures. Figure 30 shows the locations of major faults in the Springfield

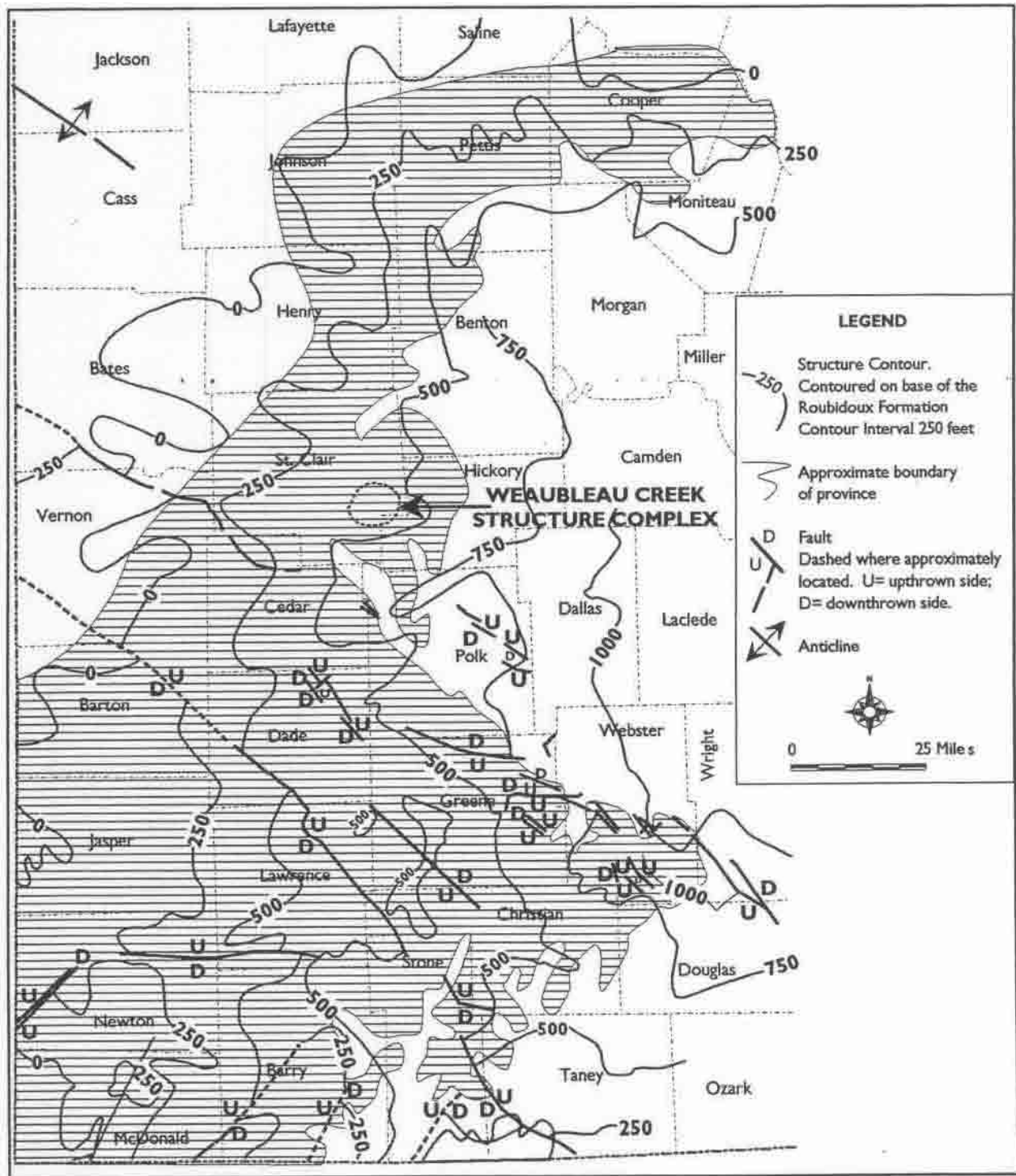


Figure 30. Structural map of the Springfield Plateau groundwater province (from McCracken, 1971).

Plateau. Faulting is commonly the result of crustal movements, and displaces adjacent blocks or bodies of rock in relation to one another. This displacement causes shattering and fracturing of the rock units adjacent to the fault plane. The larger the fault, the larger the area of shattered rock. Wells constructed along or adjacent to major fault systems generally have higher yields than normal, but they are also more likely to encounter weathered materials such as mud or clay, and have either construction or water-quality problems.

PRECAMBRIAN SYSTEM

Like in the Salem Plateau, Precambrian igneous and metamorphic rocks underlie the Paleozoic sediments throughout the Springfield Plateau groundwater province. Also, like the Salem Plateau, the Precambrian rocks are not considered to be an aquifer, and form the Basement confining unit.

CAMBRIAN SYSTEM

Lamotte/Reagan Sandstone

The Lamotte Sandstone is Late Cambrian in age and is the basal clastic unit throughout much of the Springfield Plateau groundwater province. However, in part of southwestern Missouri a second stratigraphic name, the Reagan Sandstone, is used instead of Lamotte. The stratigraphic term "Lamotte" originated in southeastern Missouri around the St. Francois Mountains area while the term "Reagan" originated in Johnson County, Oklahoma. Both names are used to describe a laterally continuous sandstone unit that extends across southern Missouri into Oklahoma and Kansas. The Lamotte and Reagan were deposited in a sea that was transgressing from east to west. Both rest unconformably on Precambrian igneous and metamorphic rocks, but the sandstone was deposited in the eastern part of the province before it was deposited in the western part. Thus, in the eastern part of the province the sandstone is much older than it is to the west.

If one uses standard stratigraphic methods and adheres to the Stratigraphic Code, it would seem almost unthinkable to give two separate stratigraphic names to what appears to be one continuous formation, especially

since the lithology does not appreciably change. The major difference between the two is that across southwestern Missouri from east to west, the unit is progressively overlain by younger rocks and the sandstone itself is progressively younger.

A formation can cross time lines and still be considered the same formation, so there appears to be little reason for the name change. However, in southwestern Missouri there are certain economic geology considerations that encourage distinguishing between the two. Several years ago, test drilling for lead and zinc mineralization was actively occurring in southwestern Missouri. Mineral companies were interested in the area where the Lamotte Sandstone is overlain by the Bonneterre Formation. The Bonneterre is commonly the host rock of Mississippi Valley Type ore deposits, and if the Bonneterre Formation is missing there is little potential for the discovery of economically valuable minerals. Carbonate rock of the Bonneterre Formation was being deposited in the eastern part of this region at the same time that sandstone was being deposited in the western part. Essentially, from east to west across the region, the Bonneterre Formation thins and is replaced by sandstone. The name "Reagan Sandstone" is used in Missouri to designate the basal Cambrian sandstone unit in the western part of the area where the Bonneterre Formation is absent. The name "Lamotte Sandstone" is used for the basal Cambrian sandstone unit in the eastern part of the province where it is overlain by Bonneterre Formation.

Although the name change may be significant in terms of mineral exploration, hydrologically the name change means very little. The Lamotte and Reagan appear to have similar hydrologic characteristics.

Bonneterre and Davis Formations and Derby-Doerun Dolomite

The lithologies or general rock characteristics of these units where they are present in southwestern Missouri are essentially the same as in the Salem Plateau. The Bonneterre is primarily a dolomite unit, the Davis a carbonate and silty, shaley carbonate, and the Derby-Doerun

a dolomite. One major exception to this is that the Davis Formation becomes less shaley and contains more limestone and dolomite in the western part of the state. In the Salem Plateau, the Davis is considered a regional aquitard due to its high shale content and subsequent low vertical permeability. In the west, where it grades to a carbonate, it may have higher vertical permeability and allow greater interchange of water between zones above and below it.

The Bonneterre, Davis, and Derby-Doerun thin from east to west across the Springfield Plateau, and may be locally absent in extreme western Missouri.

Potosi Dolomite

The Potosi Dolomite thins from east to west across the Springfield Plateau, and locally interfingers with the overlying Eminence Dolomite to produce an alternating repetition of lithologies with depth. Where present, the interval in which this interfingering occurs averages 25 to 30 ft thick. Elsewhere, where the normal sequence of rock is present, the Potosi ranges in thickness from 0 to approximately 50 ft. The overall lithology of the unit is unchanged from the Salem Plateau, being a fine- to medium-crystalline, massive- to thickly-bedded, brownish-gray dolomite that exhibits vugs or small cavities filled with quartz druse.

Eminence Dolomite

The Eminence Dolomite thins from east to west across southwestern Missouri. At Springfield, the unit is composed of about 340 ft of light-gray, fine- to medium-crystalline dolomite that generally contains less than 5 percent chert. It appears that the Eminence thickens at the expense of the underlying Potosi Dolomite, which here, is only 45 ft thick. At Noel, in McDonald County at the extreme southwestern corner of the state, a mineral exploration test hole encountered the Eminence at a depth of 1,475 ft. The unit had thinned to only 115 ft, but the underlying Potosi was found to be 70 ft thick. The lithologies of the two units are quite similar in the western part of the Springfield Plateau groundwater province.

ORDOVICIAN SYSTEM

Gasconade Dolomite and Gunter Sandstone Member

As in the Salem Plateau, the Gasconade Dolomite in the Springfield Plateau is informally divided into the upper and lower Gasconade Dolomites, and the Gunter Sandstone Member. The Gunter Sandstone Member of the lower Gasconade Dolomite has an average thickness in the Springfield Plateau of approximately 30 ft. It is the lowermost rock unit of Ordovician-age in the province. As in the Salem Plateau groundwater province, the Gunter conformably overlies the Eminence Dolomite. Over much of the province, it is composed of sandy dolomite, which ranges in sand content from about 20 to 100 percent. There are some instances where the unit contains thin beds of dolomitic sandstone, but this occurrence is rare. There does not seem to be any uniform tendency for this unit to thin appreciably from east to west as with the underlying units.

The lower Gasconade Dolomite conformably overlies the Gunter Sandstone. The unit ranges in thickness in southwestern Missouri from about 335 ft on the eastern side of the province near Springfield in Greene County, to about 240 ft in central McDonald County at the extreme southwestern corner of the state. In the eastern part of the Springfield Plateau, the upper 100-ft of the lower Gasconade typically has a high chert content, locally as much as 60 percent. In the western part of the province, however, the thickness of the chert-rich interval increases to include the upper 175 ft of the formation, but the total percentage of chert in the rock decreases somewhat.

The upper Gasconade Dolomite conformably overlies the lower Gasconade in the Springfield Plateau. It ranges in thickness, east to west across the province, from approximately 40 ft to 70 ft. Unlike the lower Gasconade, the upper Gasconade is relatively chert-free, consisting primarily of fine- to medium-crystalline, grayish-brown dolomite. The thinning of both upper and lower Gasconade dolomites is quite likely the result of the transgression of the early Ordovician sea from

east to west across the state, and the resulting shortened time span during each depositional phase.

Roubidoux Formation

The Roubidoux Formation in the Springfield Plateau loses many of the lithologic characteristics that typify it in the Salem Plateau. In the Salem Plateau, the term Roubidoux is synonymous with sandstone. In the Springfield Plateau, however, the Roubidoux is predominantly a cherty dolomite, and generally contains only scattered beds of dolomitic sandstone. Whereas sandstone may comprise 50 to 75 percent of the Roubidoux in the Salem Plateau, the Roubidoux in the Springfield Plateau may only constitute 10 percent of the total rock.

Jefferson City, Cotter and "Powell" Dolomites

The Lower Ordovician-age Jefferson City Dolomite conformably overlies the Roubidoux Formation in southwestern Missouri. Its thickness remains relatively constant across the province at about 210 ft. The unit consists of dolomite and cherty dolomite. It is recognizable in the subsurface from drilling samples by the presence of oolitic cherts. Oolites appear as very small, clustered spheroids within the chert.

Conformably overlying the Jefferson City is the Cotter Dolomite. The Cotter ranges in thickness in the Springfield Plateau from 175 ft in the east to 400 ft in the west. Its lithology is similar to that found in the Salem Plateau. It consists of dolomite and cherty dolomite with minor sandstone beds and thin partings of green shale. A most notable sandstone bed, termed the "Swan Creek," is some 3 ft to 15 ft thick. The Cotter is the oldest formation that crops out in the Springfield Plateau.

The "Powell" Dolomite is present in the subsurface of the Springfield Plateau groundwater province in the extreme southwestern part of the state where it consists of medium- to finely-crystalline dolomite with thin beds of green shale and fine-grained sandstone. Where present, it is a maximum of about 80 ft thick. It is Lower Ordovician (Canadian) age, and conformably overlies the Cotter Dolomite.

DEVONIAN/MISSISSIPPIAN SYSTEM

Chattanooga Shale

The Chattanooga Shale of late Devonian-age unconformably overlies the Jefferson City-Cotter-"Powell" sequence in the southwestern part of the Springfield Plateau groundwater province. Where present, the Chattanooga is a fissile, black, carbonaceous, sandy shale. It locally exhibits an oily or bituminous odor. Some wells penetrating the unit have encountered small quantities of free oil. The unit is thickest in McDonald County where it achieves a maximum thickness of about 30 ft. A few miles to the east in southern Barry County it thins to approximately 10 ft. It is absent throughout much of the eastern and northern part of the Springfield Plateau.

MISSISSIPPIAN SYSTEM

Compton Limestone, Sedalia Formation and Northview Formation

These formations are all included in the Chouteau Group, a sequence of Lower Mississippian-age rocks that show considerable variability in the Springfield Plateau. The Compton is a very finely-crystalline limestone, which has an abundance of finely-distributed crinoid fragments, and ranges in thickness from 5 ft to 30 ft. It is typically thin-bedded with greenish-gray shale interbeds between the limestone beds. The unit may be locally dolomitic, and where this is the case it is usually massive in appearance. The lower part of the formation is sandy in the eastern part of the province, and becomes more argillaceous or silty to the west. The Compton and the underlying formations are separated by a major unconformity.

The Sedalia Formation conformably overlies the Compton in the northern part of the province. The lithology of the Sedalia is quite similar to that of the underlying Compton, the main differences being that the Sedalia is more dolomitic, thickly-bedded and has more chert. It reaches a maximum thickness of about 50 ft in west-central Missouri. Southward from western Pettis County, the unit thins greatly, and seems to interfinger with the overlying Northview Formation (Howe, 1961). It disappears from the rock sequence to the south in Cedar County.

The Northview Formation conformably overlies the Sedalia where it is present, and also the underlying Compton due to the interfingering of the Compton and the Sedalia mentioned above. In the Greene and Webster county area it consists of two separate units, a lower shaley unit and an upper, predominantly siltstone unit. This is also one of the areas in which the Northview is at its thickest, attaining a maximum thickness of about 80 ft. In fact, this extreme thickness is part of northwest trend that extends from Greene County to Barton County. The unit thins to the north and south of this trend, and averages less than 5 ft in thickness in the northern and southern tier of counties in the province.

This Northview Formation has a highly variable lithology, ranging between greenish-brown siltstone to green, silty clay from one locality to the next. As it thins north and south from the previously mentioned trend, it becomes progressively more shaley to the north and more calcareous to the south.

Pierson Limestone, Reeds Spring Formation, Elsey Formation, and Burlington-Keokuk Limestone

The Pierson Limestone in the Springfield Plateau conformably overlies the Northview Formation, and is of Osagean- or middle Mississippian-age. It ranges in thickness from less than 5 ft to as much as 55 ft in the southern part of this province in Stone and Barry counties.

The Pierson is a medium- to massively-bedded limestone containing abundant chert in the upper part. Locally, the unit is composed of cherty, dolomitic limestone. Where the unit is thinnest, the cherty interval is missing.

The Reeds Spring Formation has an average thickness of about 100 ft in the southwestern part of the province, but thins to the northeast. In the Springfield area, the unit is only about 30 ft thick. It is absent north of the Springfield area. The Reeds Spring is composed of alternating beds of finely-crystalline limestone and dark-gray, sandy chert. Throughout its depositional area, the Reeds Spring contains almost equal amounts of limestone

and chert, and in the upper part of the formation chert is the predominant lithology.

The Elsey Formation conformably overlies the Reeds Spring, and lithologically is similar to it. They differ mainly in the type of chert they contain. The Elsey has white to grayish-white chert, which has brown mottled patches and large circular spots. Many workers simply combine the two formations because of their similarity, and call the combined unit the Elsey-Reeds Spring Formation. The Elsey has an average thickness of about 30 ft.

The Burlington and Keokuk limestones conformably overlie the Elsey in the Springfield Plateau province. They are both medium- to coarsely-crystalline limestones that are white- to light-gray and medium- to thickly-bedded. Crinoid fossils are abundant in both units, and in places the limestone is mostly composed of fossil fragments. The Keokuk, which overlies the Burlington, is slightly finer-grained and contains more chert, particularly in the lower part. Otherwise, the two units are so similar that workers usually combine the two in discussions. The Burlington-Keokuk ranges in thickness from 200 ft, near Springfield in Greene County, to approximately 100 ft near Joplin. To the south in southern Barry County, the Burlington pinches out, leaving only the Keokuk present.

Much of the karst development in the Springfield Plateau is in the Burlington-Keokuk Limestone. Most of the major caves, springs, sinkholes and losing streams are developed in this stratigraphic interval. The karst in southwestern Missouri appears younger than that in the Salem Plateau, and unlike the karst weathering to the east, karst weathering in the Springfield Plateau has not produced the thick residual cover that typifies the Salem Plateau in southeastern Missouri. Nonetheless, numerous caves, sinkholes, springs and losing streams are present in the southwestern part of the state.

In many locations where the Burlington-Keokuk are the shallowest bedrock units, their upper surface has weathered very unevenly into cutters and pinnacles (figure 31). Pinnacles stand in relief above the intervening

gulleys or cutters. The cutters typically coincide with joints, along which there has been solutional weathering. The pinnacles are essentially the bedrock pillars between the cutters, and are locally 8 to 10 ft high and a few feet to a few 10s of feet across. Travelers in southwestern Missouri can see this type of feature in the Springfield area, particularly along Interstate 44 along the northern part of the city, and also along its eastern margin on U.S. Highway 65.

Other Mississippian-Age Formations

Mississippian-age formations overlying the Burlington-Keokuk interval are of little im-

portance with regard to their groundwater possibilities. A possible exception is the Warsaw Formation, which directly overlies the Burlington-Keokuk. The lower Warsaw consists of fossiliferous limestone much like the underlying Burlington-Keokuk. The upper part of the formation is a calcarenite, and is composed of sand-size calcium carbonate grains. The unit is 150 ft thick or more in the Tri-State district in Jasper and Newton counties, but is typically much thinner. Overlying the Warsaw is a thin sequence of Mississippian rocks, which directly underlay rocks of Pennsylvanian-age. These rocks are not considered significant water-yielding units. They



Figure 31. Cutters and pinnacles in the Burlington-Keokuk Limestone along U.S. Highway 65 in Springfield. Photo by Jim Vandike.

may, however, yield small quantities of water to private wells drilled through them.

PENNSYLVANIAN SYSTEM

Undifferentiated Pennsylvanian Strata

Rocks of Pennsylvanian age form the bedrock surface in the western part of the Springfield Plateau groundwater province. In terms of physiography, the areas underlain by Pennsylvanian-age strata in this area are within the Osage Plains physiographic province. However, since the deeper aquifers in Mississippian-, Ordovician-, and Cambrian-age rock yield potable water for several miles into the Osage Plains, part of it is included in the Springfield Plateau groundwater province.

Pennsylvanian-age rocks are described in many measured stratigraphic sections, have been logged in many wells, and consist of several formally described stratigraphic units. However, in this report the Pennsylvanian formations will not be discussed individually, but instead will be discussed as a group of undifferentiated rocks. The Pennsylvanian strata range in thickness from a feather edge at their cropline, to as much as 120 ft at their western extent in the province. They are composed of sequences of siltstone, sandstone, shale and thin limestone. Locally, the shale and siltstone sequences have thin coal beds.

HYDROGEOLOGY

BASEMENT CONFINING UNIT

As in the Salem Plateau groundwater province, the thick sequence of Paleozoic rocks in the Springfield Plateau rest upon Precambrian igneous and metamorphic rock. The Precambrian rocks are mostly crystalline, and have essentially no effective porosity or permeability. They form a lower confining unit for the St. Francois aquifer that precludes further downward movement of water below that aquifer.

ST. FRANCOIS AQUIFER

As in the Salem Plateau, the St. Francois aquifer in the Springfield Plateau consists of the Bonneterre Formation and the

Lamotte/Reagan Sandstone. However, because of its depth and the generally adequate yields from shallower zones, few communities in the Salem Plateau groundwater province presently make use of the St. Francois aquifer.

One town that does is the city of Sedalia, which has four wells penetrating the Lamotte. A fifth well was planned to finish in the Lamotte, but went directly from the Bonneterre Dolomite into Precambrian basement rocks; the Lamotte Sandstone was absent at that location. At Sedalia, the Lamotte increased the overall yield of the wells, which also produce from the Ozark aquifer, an additional 100 to 200 gpm above the average of 450 gpm obtained from shallower horizons. These wells ranged in depth from 1,460 ft to 1,665 ft, with the average thickness of the Lamotte being about 220 ft. Similar yields are likely possible from the Lamotte/Reagan in other areas of southwestern Missouri.

The city of Carl Junction in Jasper County has completed two wells that penetrate the Lamotte/Reagan. As in Sedalia, yields from shallower zones were less than desired, and the additional production from the deeper aquifer increased the total yield more than 100 gpm.

The Lamotte is missing in several places in western and southwestern Missouri. One such location, recently discovered, is at the extreme eastern edge of the Springfield Plateau just northeast of Warsaw in Benton County. Here, the Missouri Department of Conservation recently finished several high-yield wells that will supply a large fish hatchery. Most of the wells penetrated the normal Ozark aquifer sequence, but at least one well encountered granite at a relatively shallow depth, less than 1,000 ft. The granite was directly overlain by Potosi Dolomite; the Davis, Bonneterre, and Lamotte (Reagan) formations were absent.

The Bonneterre Formation, Davis Formation, and Derby-Doerun Dolomite are present in places in the Springfield Plateau, but are generally poor water-yielding units. There are instances when deep wells scheduled to fully penetrate the Ozark aquifer bottom in the

middle part of the Derby-Doerun. Locally, small amounts of water are encountered but not more than 30 to 50 gpm. In most areas, though, there is no appreciable addition of water from the Derby-Doerun.

In the Springfield Plateau, the Davis Formation has less shale than areas to the east, and because of this there may be greater interchange of water here between the Ozark aquifer and the St. Francois aquifer. However, so little information is available concerning the hydraulic relationship between the two aquifers that such theories are highly speculative.

The volume of usable groundwater contained in the St. Francois aquifer in the Springfield Plateau groundwater province is estimated to be about 4.1 trillion gallons, or about 12.6 million acre-ft.

OZARK AQUIFER

The Ozark aquifer in the Springfield Plateau consists of most of the same geologic units as to the east. In ascending order it consists of the Potosi, Eminence, and Gasconade dolomites, the Roubidoux Formation, and the Jefferson City, Cotter, and locally "Powell" dolomites. Figure 32 shows the thickness of the Ozark aquifer in the Springfield Plateau groundwater province. In terms of yield, this aquifer is the most prolific one in the southwestern part of the state, and provides for municipal, industrial, and agricultural water supply throughout the region. Joplin, Neosho and Springfield each use surface water to meet some if not most of their water-supply needs, but all of these cities also have wells penetrating the Ozark aquifer that are either emergency sources of water, or supplement their surface-water supplies.

The Ozark aquifer is a confined aquifer throughout most of the province. It is bounded below by the St. Francois confining unit, principally the Derby-Doerun Dolomite and Davis Formation, and above by the Ozark confining unit, consisting of the Chattanooga Shale, Compton Limestone, Sedalia Formation, Northview Formation, and Pierson Limestone. Fully penetrating Ozark aquifer wells in the Springfield Plateau generally yield

from 200 to as much as 2,000 gpm. Yields are generally lowest in extreme western Missouri from Joplin south to McDonald County. Highest yields generally occur in the northwestern part of the plateau and in the Springfield area.

The quality of water produced from the Ozark aquifer is generally very good. It is a moderately-mineralized calcium-magnesium-bicarbonate type of water (table 11).

The Potosi interval, regardless of its lithologic character or thickness, is an important water-bearing horizon in the province. The Potosi is generally too deep for use as a water source for private domestic wells, but it is an important aquifer zone for high-yield municipal wells in the eastern part of the province. The city of Springfield in Greene County has several wells that fully penetrate the Potosi at depths averaging about 1,500 ft. These wells produce from zones between the Cotter and the base of the Potosi. Yields as high as 2,000 gpm are reported, but average yields are generally less than 1,000 gpm. West, south, and southwest from the Springfield area, the Potosi occurs at progressively greater depths. Very few water wells have been drilled into the Potosi outside of the Springfield area until fairly recently. Two Potosi wells were drilled in 1994 near Branson in southern Taney County at the eastern edge of the Springfield Plateau. Both wells encountered the base of the Potosi at a depth of nearly 2,000 ft, and had yields of more than 800 gpm. The reluctance to drill into the Potosi in southwestern Missouri where the unit is deeply buried is purely economical. The cost of drilling a 2,000-foot deep, large-diameter well containing 400 ft of pressure-grouted casing is cost prohibitive for most individuals as well as many smaller towns, industries and water districts, especially if sufficient quantities of water can be found at shallower depths.

Until recently, most high-yield Ozark aquifer wells in the Branson area bottomed in the lower Gasconade Dolomite or upper Eminence Dolomite. Yields from the intermediate-depth zones of the Ozark aquifer were sufficient. However, the recent rapid growth of the area has led to the construction of more

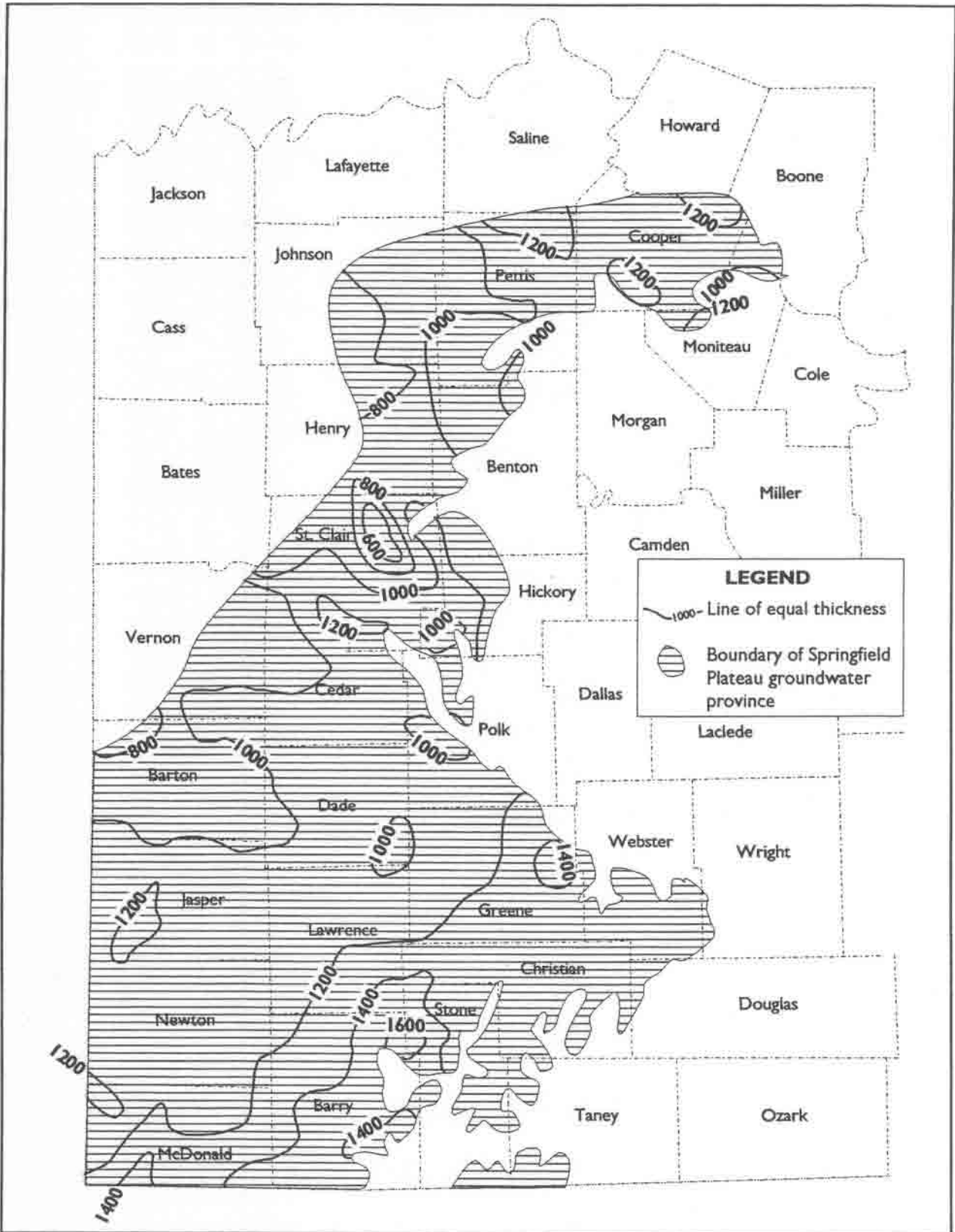


Figure 32. Map showing thickness of the Ozark aquifer in the Springfield Plateau groundwater province (from Imes, 1990).

City Water Supply	pH	Alkalinity	Iron	Manganese	Sodium	Potassium	Calcium	Magnesium	Nitrate	Sulfate	Chloride	Fluoride	Total Dissolved Solids	Total Hardness	Copper
Billings	7.8	173.	< 0.10	0.02	2.1	1.0	36.0	20.9	< 0.05	13.0	2.8	< 0.10	250.	176.	0.01
Branson	7.4	86.	< 0.10	< 0.02	2.9	1.8	32.9	4.7	0.18	11.0	8.0	< 0.20	182.	102.	0.05
Carthage	7.9	164.	< 0.10	< 0.02	10.2	1.9	23.7	16.6	< 0.05	-	-	0.26	-	150.	0.05
Clever	8.0	120.	0.15	0.03	1.6	1.0	28.6	15.1	< 0.05	14.0	< 2.0	0.11	162.	134.	0.01
Crane	7.7	180.	< 0.10	0.02	2.4	1.4	38.6	20.4	< 0.05	< 10.0	< 2.0	< 0.20	201.	180.	0.05
Galena	7.8	145.	< 0.10	< 0.02	1.3	1.1	29.2	17.6	< 0.05	11.0	< 2.0	< 0.20	159.	145.	0.05
Joplin	7.4	94.	< 0.10	< 0.02	4.9	2.6	40.4	2.2	2.20	14.0	11.0	< 0.20	146.	110.	0.05
Lamar	8.4	60.	< 0.10	< 0.02	23.0	5.0	31.9	5.0	< 0.05	91.0	10.0	0.64	217.	98.	0.05
Mindenmines	7.8	268.	< 0.10	< 0.02	80.0	5.2	39.3	17.1	< 0.05	15.0	66.0	0.97	399.	169.	0.13
Neosho	7.4	115.	< 0.10	< 0.02	9.9	4.0	50.6	3.4	2.10	17.0	15.0	< 0.20	190.	140.	0.05
Nixa	7.8	165.	< 0.10	< 0.02	2.0	1.4	38.5	19.8	< 0.05	10.0	2.0	0.10	218.	178.	0.01
Noel	8.0	125.	< 0.10	< 0.02	54.4	2.8	24.3	11.0	< 0.05	16.0	67.0	0.85	279.	106.	0.01
Ozark	7.9	135.	< 0.10	< 0.02	1.3	1.1	31.6	16.2	< 0.05	14.0	< 2.0	< 0.10	166.	146.	0.01
Pleasant Hope	7.7	164.	0.27	< 0.02	1.6	0.9	35.0	17.5	< 0.05	10.0	< 2.0	< 0.20	202.	160.	0.05
Republic	7.8	147.	< 0.10	< 0.02	3.2	1.4	35.3	16.8	< 0.05	10.0	< 2.0	1.00	173.	157.	0.01
Seligman	7.8	153.	< 0.10	< 0.02	2.2	1.1	40.2	19.3	< 0.05	25.0	< 2.0	< 0.10	230.	180.	0.01
Strafford	7.6	136.	< 0.20	< 0.02	2.9	1.2	31.8	15.5	< 0.05	16.0	2.0	< 0.10	174.	143.	0.01
Walnut Grove	7.8	148.	0.10	< 0.20	1.7	1.3	33.9	17.2	< 0.05	< 10.0	3.0	< 0.10	202.	156.	0.01

Analyses expressed in milligrams per liter (mg/L)

Table 11. Chemical analysis of water from selected Ozark aquifer wells in the Springfield Plateau groundwater province (from Department of Natural Resources, 1991).

and deeper Ozark aquifer wells, resulting in a lowering of groundwater levels in that aquifer in parts of western and southern Taney County. Drawdown has also locally decreased the saturated thickness of the Ozark aquifer, and thus its transmissivity. As transmissivity decreases, well yield decreases and drawdown increases, as does pumping cost since the water has to be raised a greater vertical distance. Figure 33 is a hydrograph from city of Branson well #4, which has been used as a groundwater-level observation well since 1993. This well is about 2 miles from the major pumping area in Branson, but nonetheless shows seasonal water-level changes of more than 50 ft.

In terms of total water resources, southern Taney and Stone counties are relatively water-rich; Table Rock, Taneycomo and Bull Shoals lakes bisect the area. With the exception of the immediate Branson area where overproduction has caused a lowering of groundwater levels, groundwater resources are still excellent in this area. There is more than enough water to meet present and reasonable future demands; the problem is pri-

marily with distributing the water. Groundwater has historically been used almost exclusively in this area because it was relatively inexpensive to obtain. Although drilling a deep, high-yield well suitable for public-water supply use is far from free, it is much less expensive than constructing a reservoir, or a pipeline to an existing reservoir, and building and maintaining a surface-water treatment plant. With few exceptions, raw water from the Ozark aquifer in this area requires no treatment to meet public drinking water standards.

The Ozark aquifer in southwestern Missouri is a confined aquifer, and except for a few areas where overproduction has lowered its potentiometric surface to below the base of the Ozark confining unit, water in an unpumped well will rise in the drill hole above the top of the aquifer. When a well is pumped, water-level in the aquifer adjacent to the well begins to decline. The rate of decline depends on the pumping rate, aquifer transmissivity and storativity coefficients, and how long the well is pumped. The drawdown is greatest in the pumped well, and decreases

with distance away from the well. This draw-down gradient extends in all directions away from the pumped well, and is roughly cone shaped. The terms *cone of influence*, *draw-down cone*, *cone of depression*, and *radius of influence* are all terms which describe the same phenomena (figure 34).

Currently in the Branson area, and historically in the Springfield area, the depression cones of numerous wells have coalesced to form a much larger, more regional drawdown cone—the result of pumping from numerous high-yield wells all producing from the same aquifer. The results are deeper pumping levels for all wells located within the cone, reduced yields for most wells, higher pumping costs to produce the same quantity of water, and the danger that water levels in

some wells will drop below the effective depth to which pumps can be lowered. In the case of the Springfield or Greene County cone of influence, the geographic size of the cone is essentially the size of the entire county. Groundwater-level decline in the center of the pumping cone in Springfield is about 500 ft. In other words, during static or nonpumping conditions, the water level in a well in downtown Springfield is about 500 ft deeper than what it would have been prior to extensive groundwater usage. Most of the heavy pumping is done by industries that use large volumes of water, coupled with pumpage of municipal water in north Springfield.

The Branson area has only recently experienced the effects of extensive groundwater use and the resulting lowered groundwater

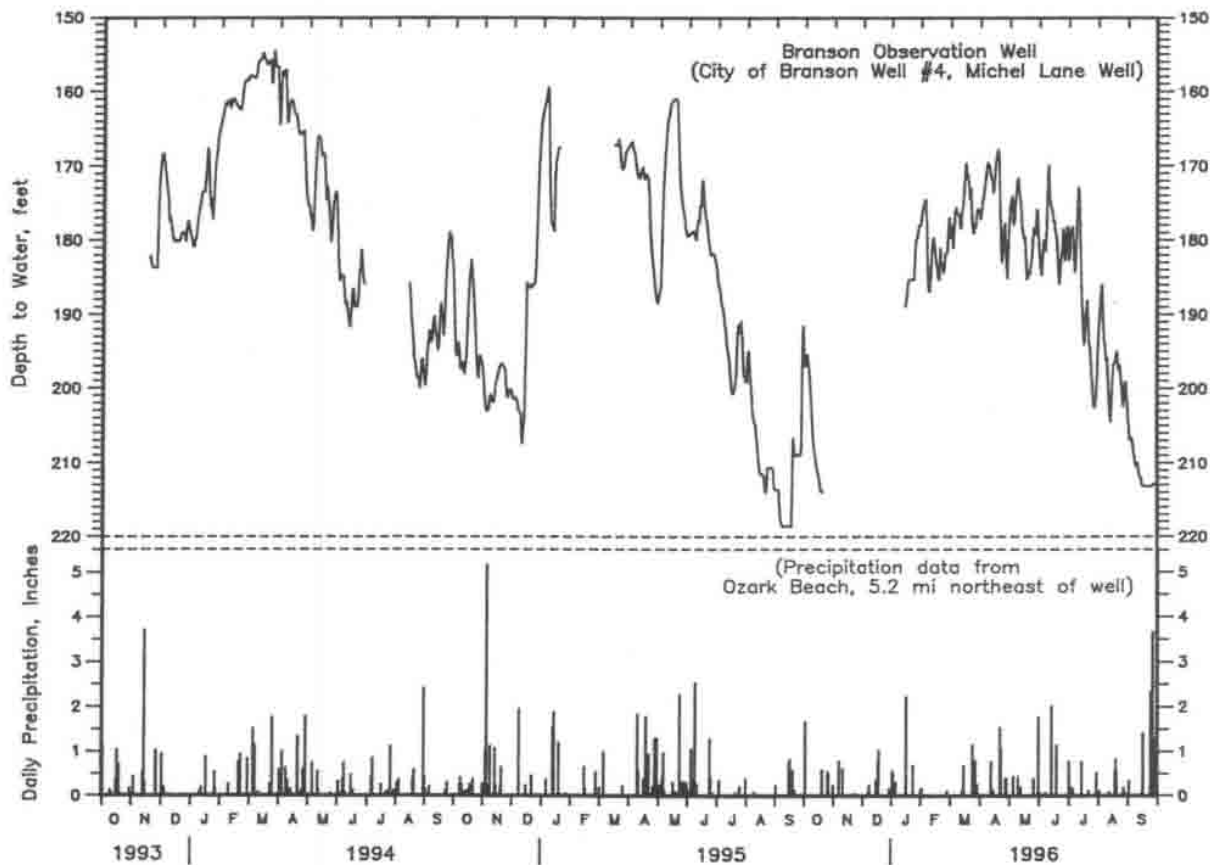


Figure 33. Groundwater-level hydrograph, Branson observation well, Taney County.

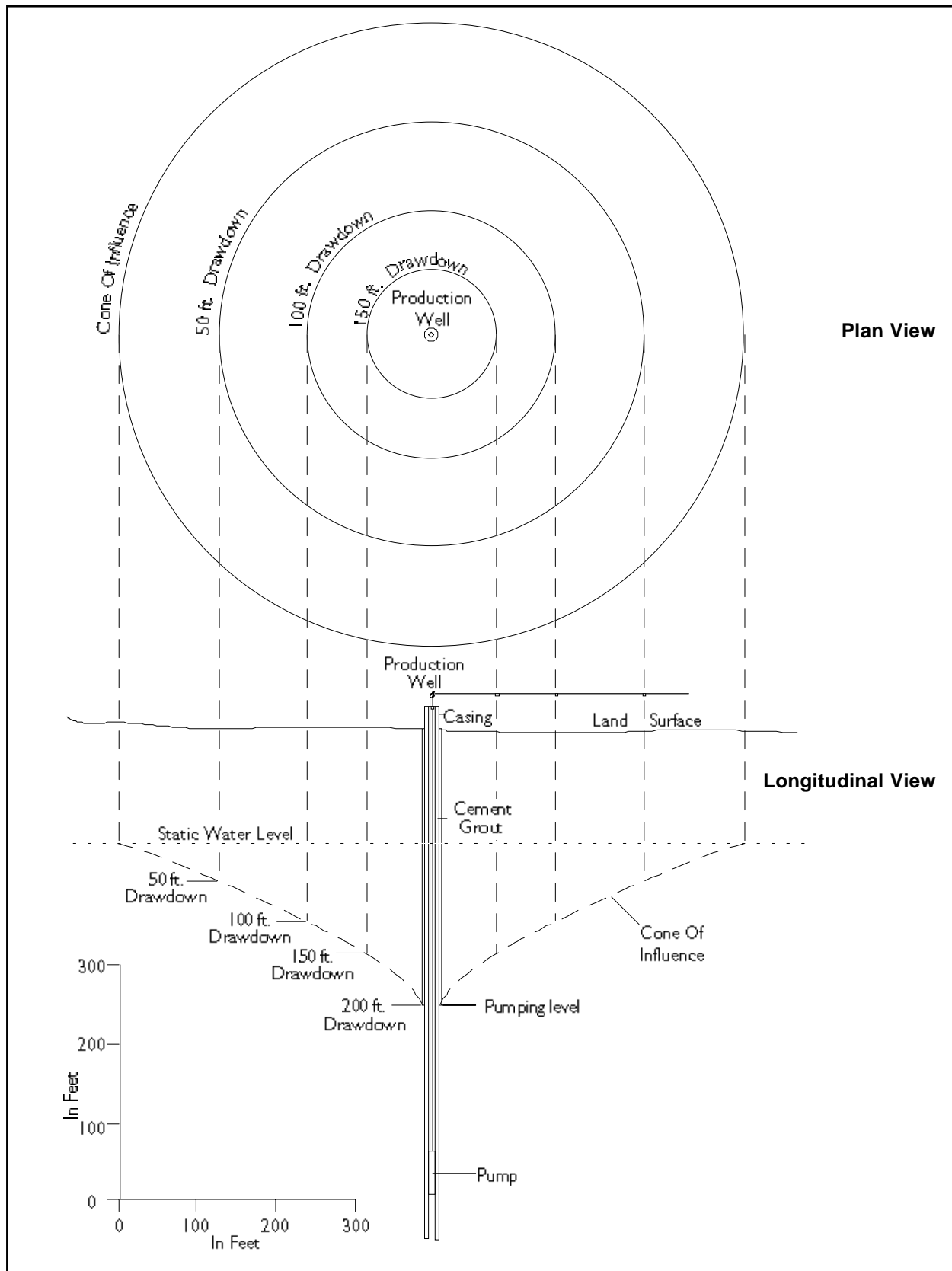


Figure 34. Idealized cone of influence from pumpage of a high-yield well.

levels. If this trend continues, the Potosi Dolomite will become increasingly important as a source for large volumes of water, regardless of the well construction costs.

Water quality from the Potosi Dolomite where utilized in the Springfield Plateau groundwater province is good, although total dissolved solids in carbonate aquifers tend to be high enough to have to classify them as high in carbonate hardness.

The Eminence Dolomite, although deeply buried in the Springfield Province, is not considered to be a prolific aquifer. The Eminence generally contributes only about 100 gpm to wells that penetrate it. The reason why this unit, which attains a thickness of more than 300 ft, should not have a higher yield is not clear. One reason may be that the Eminence has a low chert content, and has not developed the high fracture permeability needed to store and transmit large volumes of water. Units with a higher chert content such as the Roubidoux Formation, lower Gasconade Dolomite, and Potosi Dolomite, seem to transmit water more freely. This may be due to fracturing in chert beds that tend to have more open space, and which do not refill with precipitated calcium carbonate, as do fractures in limestone and dolomite. The precipitation of calcium carbonate in carbonate-rock aquifers is quite evident in many older wells where production has declined steadily over many years even though the nonpumping water levels in the wells remain nearly the same. Acidizing the wells using hydrochloric acid dissolves the precipitated carbonate, and normally restores production to its original value.

The Gunter, although relatively thin in comparison with the other aquifer units in the province, is a frequent target zone for many municipal wells. Yields of wells penetrating the unit range from 300 gpm to 500 gpm (figure 35). These values, however, are composite yields of all the formations the well is open to. Yields of water from the Gunter alone, probably range from 25 gpm to 150 gpm.

The lower Gasconade Dolomite is not typically a principal target zone for high-yield

wells in the Springfield Plateau groundwater province. Very few wells are constructed to use only this formation as a source for water. Since it occurs at depths beyond the economic capabilities of domestic well owners, it is also not a zone that is used appreciably for low-yielding wells. However, since in all cases it is below the permanently saturated zone, and has a substantial thickness of fractured dolomite with good vertical and horizontal permeabilities, it probably ultimately contributes large volumes of water due to its storage capabilities. The ultimate yield of any deep well in the Ozarks is the sum of the yields of individual water-bearing zones. So, even though the lower Gasconade lacks the production necessary to make it an attractive target zone for high yield wells, it nonetheless contributes to the production of any well that penetrates it.

The upper Gasconade Dolomite is not considered an important aquifer unit in the province. Wells drilled through the upper Gasconade seldom encounter appreciable additional yield in the unit.

The Roubidoux Formation in the Springfield Plateau is a very important aquifer unit. Many high-yield wells supplying communities, industries and irrigation use the Roubidoux as a primary source. In some instances in the Springfield area, some private domestic wells are drilled into the Roubidoux. These wells are much deeper than is typical for private wells, but in some instances the Roubidoux is the first significant water encountered. It is the youngest and shallowest high-yielding zone in the Ozark aquifer (Imes, 1990). Ordovician-age rocks that overlie the Roubidoux are much less permeable, and generally cannot supply more than 40 to 50 gpm.

Yields of the Roubidoux in this province range from approximately 60 gpm throughout much of the region to as much as 200 gpm in the extreme southwest corner of the state. Yields from the Roubidoux in the Springfield Plateau groundwater province are higher than in the Salem Plateau for at least two reasons. First, the Roubidoux is more deeply buried

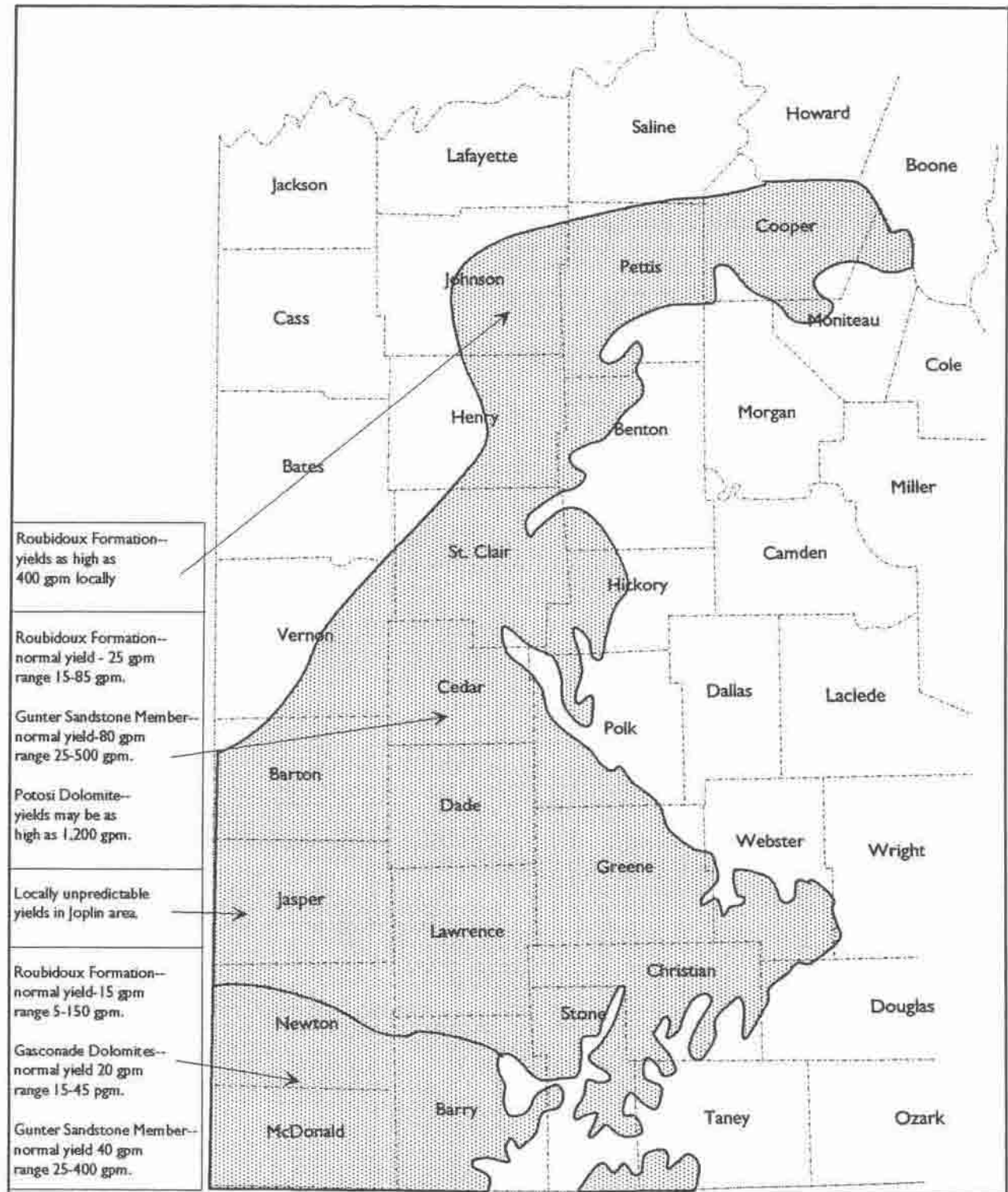


Figure 35. Yields of aquifers in Springfield Plateau groundwater province (modified from Knight, 1961).

and is well below the potentiometric surface in the Springfield Plateau, and is not as readily affected by local influences such as seasonal drought. In the Salem Plateau, the Roubidoux commonly crops out in major valleys, and groundwater gradients in shallow zones here are commonly controlled by topography. Hence, seasonal water-level fluctuations and natural drainage of the unit takes place. The second reason may be that the lithology of the unit in southwestern Missouri is much different than in most of the Salem Plateau. Here, it contains only minor amounts of sandstone, and the unit can develop greater secondary permeability due to dissolution of carbonate rock along fractures, bedding planes, and other discrete, interconnected openings. Sandstone beds in the Roubidoux are much less likely to develop high secondary permeability.

Water quality of groundwater contained in the Roubidoux is quite good. It is a calcium-magnesium bicarbonate type of water with total dissolve solids ranging between 250 mg/L and 350 mg/L.

The Jefferson City, Cotter, and "Powell" dolomites are widely used for domestic and farm water supply in southwestern Missouri, but are not considered to be high-yielding aquifer zones. They are penetrated by all high-yield Ozark aquifer wells drilled in the province, and may add a few gallons a minute to the total yield of the well. But most of the production is from the Roubidoux Formation, lower Gasconade Dolomite, Gunter Sandstone Member and Potosi Dolomite. Although many private domestic wells use the Jefferson City, Cotter, and "Powell" dolomites as a source of groundwater, there is no consistency in the capabilities of these units to yield water. All of the units have thin shale interbeds. Where the units have been fractured and subsurface weathering has occurred, there is commonly a great deal of fine, insoluble material left as a residual product. Quite possibly, any permeability created by fracturing of the rock is offset by the insoluble fines left behind by movement of water through the crevices. This same

propensity for leaving large volumes of fines behind in the form of mud is very evident.

In the Springfield area, there is a major lithologic change in the Cotter Dolomite that deserves mention. In this area, there is a sandstone unit in the Cotter called the Swan Creek Sandstone that is capable of yielding from about 5 gpm to 25 gpm. Historically, many private domestic wells have been drilled into the Swan Creek. Most contain minimal casing to also take advantage of shallower water-bearing zones in the Mississippian-age rock. This practice has caused many problems, particularly in the Springfield area, where urbanization in the karst areas has caused contamination of the shallower aquifer zones. Since the Swan Creek wells contained little casing, contaminated groundwater was able to enter the wells and to locally cause contamination of the Swan Creek interval. For many years, it has been common practice to case public water supply wells below the Swan Creek Sandstone to help preclude contaminants from affecting the deeper wells. Today, private domestic wells in much of Greene and northern Christian counties must be cased below the Northview Formation to help prevent contamination of the Ozark aquifer in that area.

The direction of groundwater flow in the Ozark aquifer in the Springfield Plateau is controlled by the same factors that control flow in the Salem Plateau. Deep flow directions are generally to the west-northwest. Hydraulic gradients in the Ozark aquifer are much lower here than to the east. As the western margin of the gradients become much lower, the groundwater velocities also decrease. It appears that in the vicinity of the freshwater-salinewater transition zone, gradients and flow rates are at their lowest.

The Ozark aquifer is used for municipal, industrial, and agricultural water supply throughout the Springfield Plateau. The aquifer receives recharge in two ways. Regionally, downward movement of water from the Springfield Plateau aquifer, through the Ozark confining unit, and into the Ozark aquifer provides a large volume of recharge. In

addition, there is groundwater recharge by lateral movement of water from the Ozark aquifer outcrop area in the Salem Plateau. The downward movement of water through the Ozark confining unit is controlled by three factors: the thickness of the Northview Formation and other units comprising the Ozark confining unit, the hydraulic conductivity of the Ozark confining unit and the difference in water levels between the Springfield Plateau aquifer and Ozark aquifer. Recharge is probably greatest where the confining unit is the thinnest and where the potentiometric surface of the Ozark aquifer is considerably lower than that of the Springfield Plateau aquifer. Downward flow gradients exist across the Ozark confining unit throughout much of southwest Missouri, especially in areas such as Springfield where extensive pumping of the Ozark aquifer has lowered the potentiometric surface of the Ozark aquifer to well below that of the Springfield Plateau aquifer. However, in some areas, particularly along the valleys of major rivers away from pumping centers, the potentiometric surface of the Ozark aquifer is above that of the Springfield Plateau aquifer, and an upward flow gradient exists.

If large volumes of groundwater are pumped in areas with little or no recharge, the results would be similar to what has occurred in the Ogallala aquifer in Texas, Oklahoma, and Kansas, and in the Dakota Sandstone aquifer in South Dakota. In those areas, groundwater recharge rates are very low, and the water is essentially being mined. Such is not the case in the Springfield Plateau. Granted, there are places where there has been significant groundwater-level decline in the Ozark aquifer, but it has occurred because groundwater production has locally exceeded recharge. In most areas of the Springfield Plateau, water levels in the Ozark aquifer have not changed more than a few feet in the past 50 years.

Agricultural irrigation has been widely used for the past 25 years in Barton, Vernon, Dade, and Cedar counties. There has been a gradual lowering of water levels in the Ozark aquifer, but surprisingly little when compared

to the volume of water produced. Groundwater levels in irrigation areas decline several feet during the irrigation season. After the irrigation season is over, groundwater levels recover somewhat, but not quite to the previous pre-irrigation level. Thus, there has been a cumulative drawdown effect; the levels at the end of the successive irrigation seasons are a little lower than the previous year (figure 36). Historically, irrigation in southwestern Missouri has been primarily supplemental in nature. It would seem that if irrigation was used only to supplement seasonal rainfall, significant water level recovery would occur if several abnormally wet years were to occur. Pumpage of irrigation water would be minimal, and recharge could occur unimpeded. However, supplemental irrigation is used nearly every year because even during wet years, July and August precipitation is typically below optimal conditions, and there is a crop-yield loss unless supplemental water is applied. Furthermore, new crops, such as cucumbers, have been introduced in this area and require considerably more water than corn and soybeans.

For many years, there has been a slow, steady decline of the Ozark aquifer potentiometric surface in southwestern Missouri from about McDonald County to Jasper County. Since 1962, groundwater levels have been monitored in this area using an abandoned municipal well at Noel in McDonald County, near the southwest corner of the state. The well is 850 ft deep and is open to the Cotter and Jefferson City dolomites and the Roubidoux Formation. It contains 99 ft of casing, and is cased through the Chattanooga Shale. When this well was drilled in 1931 for the Noel Water Company, it was a flowing artesian well that discharged about 60 gpm without pumping. Static water level of the well was several feet above land surface. Water level in the well decreased to the point that it ceased flowing in the late 1950s. In May of 1962 when it was converted into an observation well, depth to water in the well was 48.7 ft. Today, water level in the well averages about 270 ft below land surface (figure 37).

Much of the water-level decline is thought to be due to municipal well pumpage at Miami, Oklahoma, about 24 miles northwest of Noel. However, during the past two decades there has been considerable groundwater use a few miles south of Noel at large retirement developments in northern Arkansas, as well as from large poultry operations in the McDonald County area.

Estimates indicate that the Ozark aquifer is the most significant aquifer in the Springfield Plateau groundwater province. It contains an estimated 112.6 trillion gallons, or about 346 million acre-ft of usable water.

OZARK CONFINING UNIT

Between the top of the Ozark aquifer and the base of the Springfield Plateau aquifer is a series of low-permeability formations that

greatly restrict the vertical interchange of water between the two aquifers. These consist in ascending order of the Chattanooga Shale, the Compton Limestone, the Sedalia Formation, the Northview Formation, and locally the Pierson Limestone. Not all of these units are present throughout the Springfield Plateau, but in most places there is an adequate thickness of them to limit vertical groundwater movement.

The Chattanooga Shale is thickest in the extreme southwestern corner of the state, particularly in McDonald County. It is a very effective aquitard here, but also can cause water quality problems in wells that penetrate it. The Chattanooga is an organic-rich shale. Water having been in contact with it typically contains increased sulfate, may have appreciable concentrations of hydrogen sulfide,

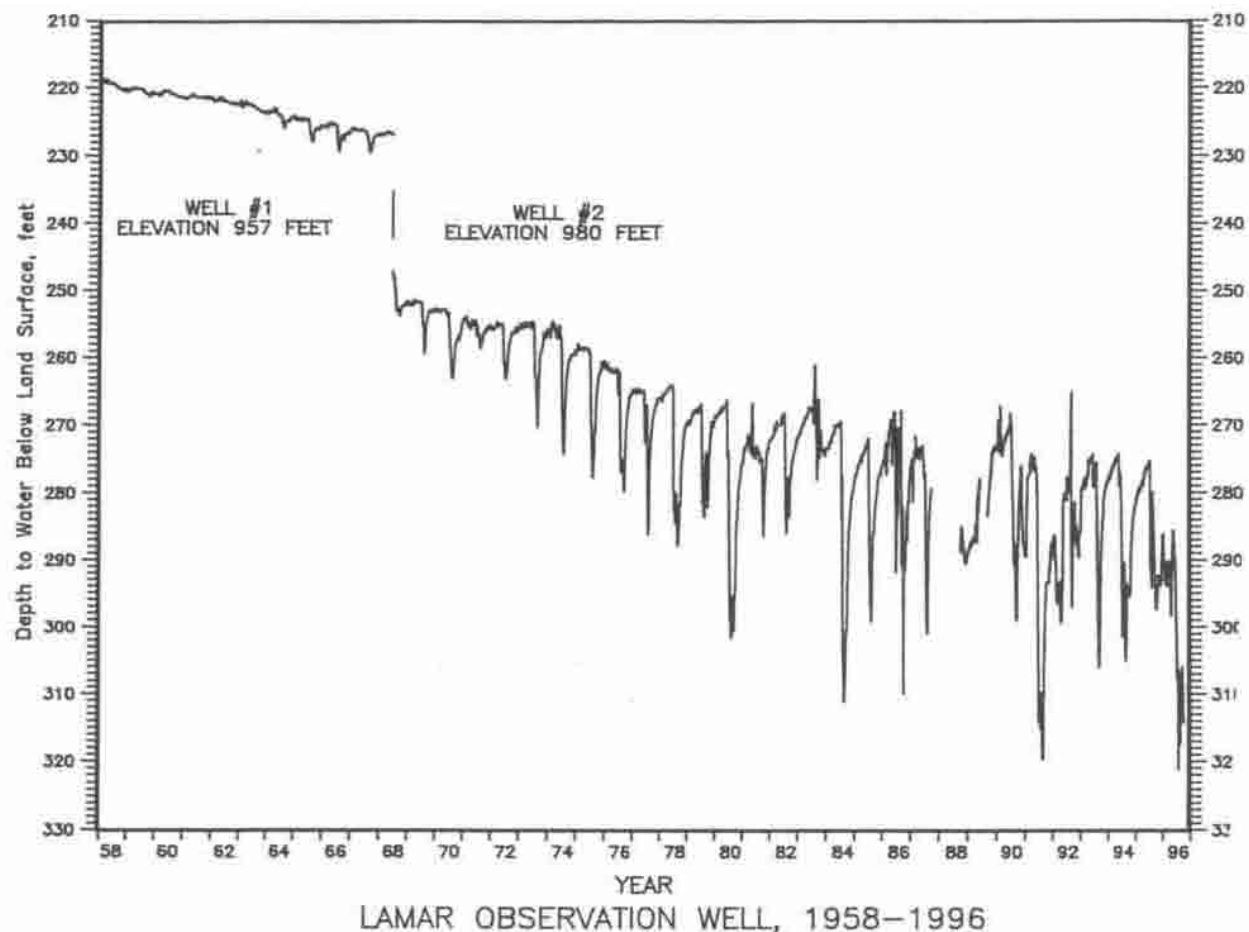


Figure 36. Groundwater-level hydrograph, Lamar observation well, Barton County.

and have an oily, disagreeable taste. Wells that penetrate the Chattanooga should be cased at least several feet below it and be adequately sealed to help prevent these types of water-quality problems.

The Compton Limestone, Sedalia Formation, and Northview Formation all have very low vertical permeabilities, which greatly restricts the vertical movement of water through them. They are, however, not considered to be aquicludes. Aquicludes are water-saturated geologic units that do not transmit significant quantities of water under ordinary hydraulic gradients (Freeze and Cherry, 1979). They are considered aquitards; their permeabilities are too low for the units to yield significant water to wells, but regionally they allow considerable water movement through them. Over a very large geographic area, this

will allow significant recharge of the Ozark aquifer to occur.

The vertical hydraulic conductivity of the Ozark confining unit has been estimated by several workers using a variety of methods, but has not been directly measured in most areas. Most of the data are from the Springfield area, where several regional groundwater studies have been conducted in the past 20 years. Emmett and others (1978) estimated the vertical hydraulic conductivity of the Northview Formation in the Springfield area to be about 1×10^{-9} ft/sec. Imes (1989) estimated the vertical hydraulic conductivity using a regional groundwater-flow model of the Ozark Plateau. A hydraulic conductivity of from 1×10^{-8} ft/sec to about 5×10^{-8} ft/sec was calculated. In either case, the hydraulic conductivity of the Ozark confining unit is several orders of

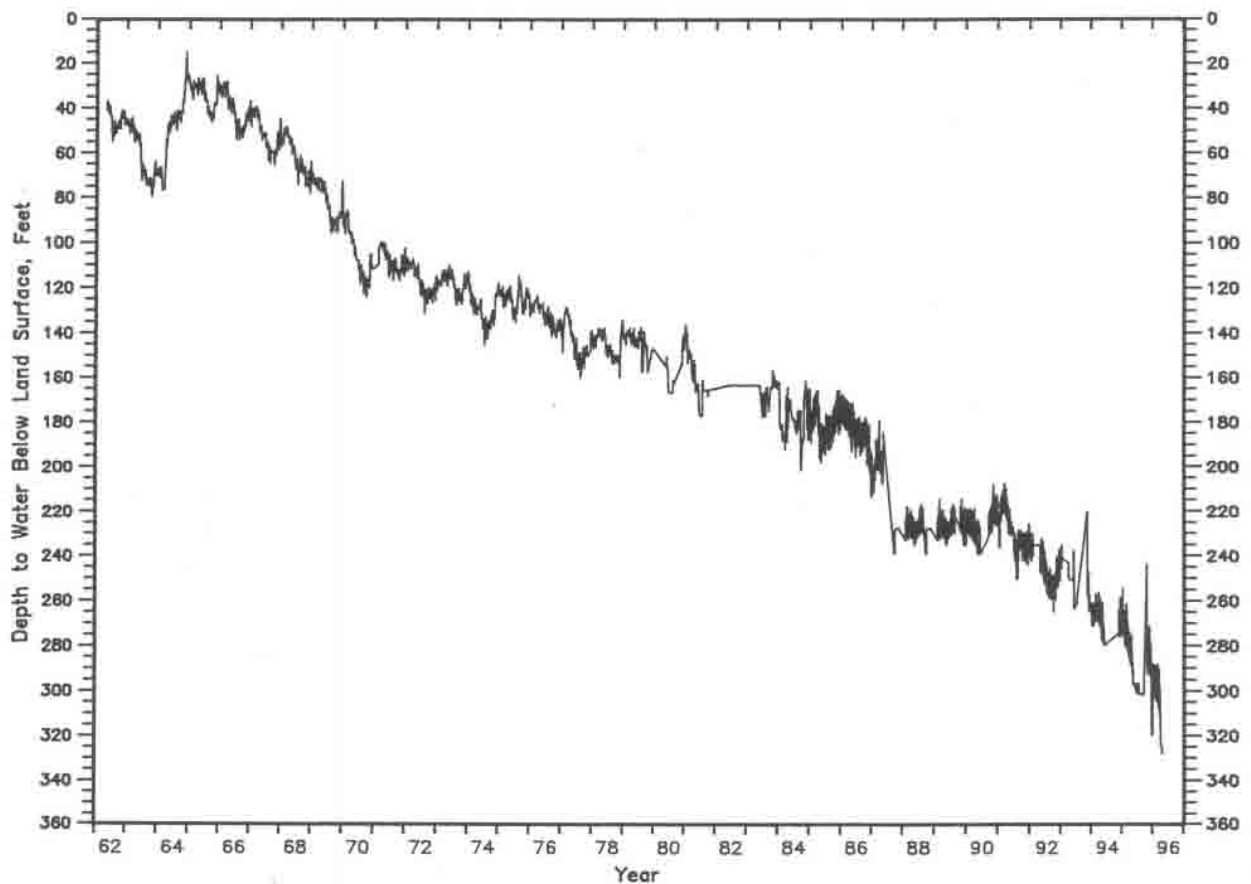


Figure 37. Groundwater-level hydrograph, Noel observation well, McDonald County.

magnitude less than the aquifer units above and below it.

There are numerous faults and other structural features in the Springfield Plateau. Several of the fault systems are known to have a significant affect on aquifer characteristics and groundwater conditions. The permeability produced by faulting varies with location. In places, deep circulation of groundwater in association with faulting can produce large conduit-type openings, and large volumes of residual mud. If water chemistry allows, calcium carbonate may be deposited in the open space. Deposition of this type may completely fill or "heal" the secondary porosity openings produced by faulting, and may form a barrier to groundwater flow. In some instances, a groundwater barrier along the strike of a fault produces a situation where groundwater levels are greatly different from one side of the fault to the other.

In the Chesapeake area of Lawrence County, several Ozark aquifer wells are used to help supply a large Missouri Department of Conservation fish hatchery. The site is bisected by the northwest-trending Chesapeake fault, which is probably the longest and most prominent structural feature in the Springfield Plateau. Water levels, yield characteristics, and water turbidity differs between wells that are only a short distance apart but on opposite sides of the fault.

In some areas, studies have revealed that there is a direct connection between the Springfield Plateau aquifer and the Ozark aquifer. A few miles south of Cassville in Barry County is a large, gently rolling area called the Washburn prairie. The area is underlain by Burlington-Keokuk Limestone, and much of the gently rolling topography is due to large sinkholes developed in the limestone bedrock. Fluorescent dye injected into a sinkhole in this area on April 14, 1993, reappeared between two and eight days later at Roaring River Spring, 6.25 miles to the southeast (figure 38). Roaring River Spring discharges from solution-enlarged openings developed in the Jefferson City and Cotter dolomites. Divers have been able to descend more than 100 ft in the conduit system

feeding the spring (Vineyard and Feder, 1982). The elevation of the rise pool at Roaring River Spring is more than 400 ft below the elevation of the bottom of the sinkhole where the dye was injected. To reappear at Roaring River Spring, the dye had to travel horizontally at least 6.25 miles, and move vertically through more than 400 ft of rock, including the zone forming the Ozark confining unit, all in a period of less than eight days. At this location, the Ozark confining unit does not appear to be a significant deterrent to communication of water between the Springfield Plateau and Ozark aquifers. Water analyses of Roaring River Spring show that the water has a calcium/magnesium ratio that is considerably higher than expected from a spring discharging from a dolomite aquifer, further evidence that a significant part of the spring's recharge is water that has passed through the Mississippian-age limestones.

This can also be seen at Marvel Cave, located at Silver Dollar City near Branson. The only natural entrance to the cave is a sinkhole developed in the Mississippian-age Reeds Spring Formation. Visitors descend several flights of stairs in the large entrance room before reaching the floor, and the trail from the stairs also continues to lead downward. From the entrance to the low point of the entrance room is a vertical distance of about 180 ft. In the entrance room, the visitor passes through the Reeds Spring Formation, Pierson Limestone, Northview Formation, Compton Limestone, and finally into the Cotter Dolomite. The total vertical extent of the cave is about 380 ft, and it bottoms in the Cotter Dolomite.

SPRINGFIELD PLATEAU AQUIFER

The Springfield Plateau aquifer consists of a sequence of cherty limestones of Mississippian age. Depending on location, the aquifer includes the Elsey Formation, Reeds Spring Formation, Grand Falls Chert, Burlington-Keokuk Limestone, and Warsaw Formation. The Pierson Limestone is considered by some to belong to the Ozark confining unit. However, small amounts of water are available from the Pierson (Imes, 1990b), and

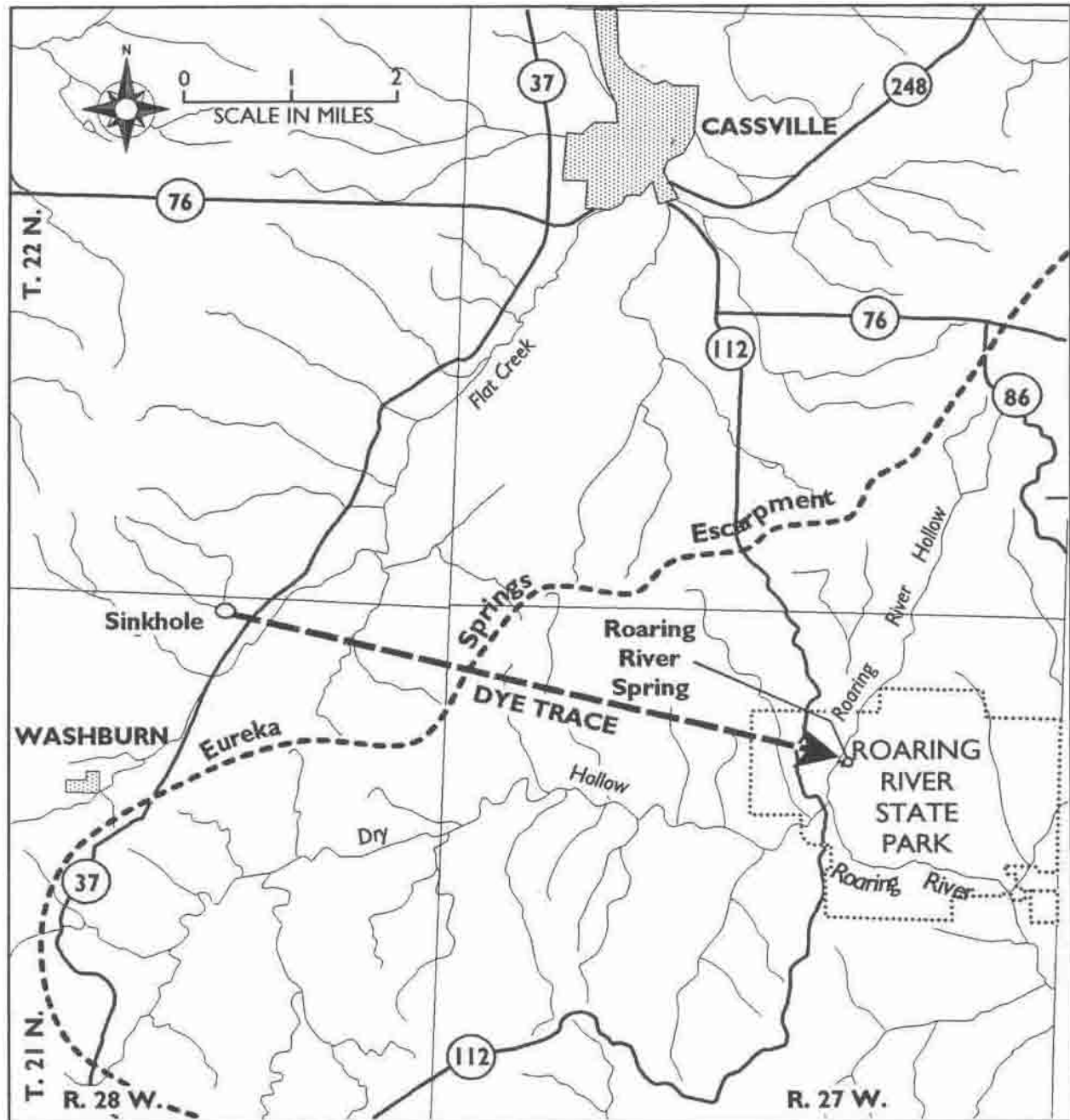


Figure 38. Dye trace from Washburn Prairie to Roaring River Spring, Barry County.

so in this report it will be included with the Springfield Plateau aquifer. Thickness of the aquifer varies from a feather edge at the eastern margin of the Springfield Plateau to more than 400 ft.

All of the Mississippian formations have the potential to yield water in small quantities to private domestic wells in this province. The high chert contents of the Reeds Spring and the lower part of the Burlington-Keokuk exhibit fracture permeability that transmits water freely, and the relatively chert-free limestone sequences in the Burlington-Keokuk have well developed solution-enlarged karst features that can also rapidly transmit large volumes of water. However, even combined, these units will not typically yield more than 30 gpm, and generally less than 15 gpm.

Like the Ozark aquifer in the Salem Plateau, the Springfield Plateau aquifer in southwestern Missouri is unconfined throughout most of the region, and is recharged primarily by precipitation in the outcrop area. Diffuse recharge moving through residual materials probably adds more water to storage than does discrete recharge from losing streams or through sinkholes. Recharge in the western part of the Springfield Plateau province is greatly restricted by the overlying low-permeability Pennsylvanian deposits. Most recharge, which does take place here, is probably the result of horizontal flow of groundwater from the Mississippian rock outcrop area to the east where the Pennsylvanian strata are absent.

The chemical quality of water from the Springfield Plateau aquifer is generally good throughout the province. The water is normally a moderately-mineralized calcium-bicarbonate type. However, since the shallow aquifer is unconfined and there is widespread karst development in the region, there have been numerous instances of groundwater contamination that have affected both wells and springs.

At the western edge of the province, in the vicinity of the freshwater-salinewater transition zone, total dissolved solids increase, and locally there are elevated levels of hydrogen sulfide gas. Associated with the H_2S gas

there is locally elevated levels of radionuclides. The direction of groundwater movement in the Springfield Plateau aquifer is generally westerly. However, topography and karst development have a profound influence over flow directions in that part of the aquifer that is less than 200 ft below land surface. Groundwater gradients in the Springfield Plateau aquifer appear to be relatively steep, particularly in those areas with more surface relief. Travel times for water from recharge to discharge point are relatively fast, especially in karst areas.

The karst development in the shallow limestone units, particularly in the Burlington-Keokuk, allows rapid discrete groundwater recharge following precipitation. Karst features are present in most of the Springfield Plateau, but are most prominent in Greene and northern Christian counties where there are numerous caves, sinkholes, losing streams and springs. Unlike the Salem Plateau, where caves are mostly abandoned groundwater pathways, in the Springfield Plateau the caves are often active groundwater conduits, and in some cases it is possible to follow an entire karst groundwater system from sinkhole through cave to spring outlet. This is nearly the case with Smalley Sinkhole Cave and Fantastic Caverns just north of Springfield in Greene County. Smalley Sinkhole Cave is entered through a large, open sinkhole in the base of a normally dry valley. The cave can be traversed for a considerable distance toward Fantastic Caverns, but the two have only been connected using fluorescent dyes. The water exits Fantastic Caverns at a spring overlooking the Sac River, a short distance upstream from the cave entrance. Except for a short distance between the two caves and between the downstream limit of human exploration and the spring in Fantastic Caverns, this system is traversable from recharge point to discharge point.

The rapid movement of water from surface recharge sources has presented water quality problems in part of the Springfield Plateau, particularly near Springfield. During the latter part of the nineteenth century and up

to the mid-1950s, the Springfield Plateau aquifer was an important source of domestic water for rural residents. Although always vulnerable to contamination due to its open nature, as urbanization increased in the Springfield area this sequence of rock became increasingly impacted by man's activities. Many shallow wells in the area became contaminated with not only bacteria, but also gasoline, industrial chemicals and, in some cases, raw sewage.

As early as the 1950s, residents constructing wells were advised to drill and case them deeper to help prevent them from being contaminated. However, there were no well construction regulations that mandated this until the Missouri Well Drillers Act was passed in 1985. Regulations approved in 1987 established a sensitive area that includes most of Greene and the northern part of Christian counties. Private domestic wells within this area must be constructed to much more stringent standards than wells in other, less populated areas. Essentially, regulations require that the wells be cased and grouted through the Ozark confining unit, and produce from the Ozark aquifer. As a result of this, the incidence of private well contamination has been reduced greatly in the Springfield area, even though rural population density continues to increase.

Although not as prolific as the St. Francois and Ozark aquifers in this region, the Springfield Plateau aquifer still contains an impressive volume of groundwater in storage, an estimated 5.7 trillion gallons, or about 17.6 million acre-ft. Even though it is less than the deeper, higher-yielding aquifers, its shallow depth and ease of availability will continue to make it a widely used source for private domestic and farm water supply.

WESTERN INTERIOR PLAINS CONFINING SYSTEM

At the western margin of the Springfield Plateau, the Springfield Plateau aquifer is confined on top by the Western Interior Plains confining system. In Missouri, this confining system consists of numerous Pennsylvanian-age formations consisting of relatively thin shale, limestone and sandstone units and several coal beds. Thickness of the Pennsylvanian

strata in the Springfield Plateau varies from zero to more than 200 ft.

The vertical and horizontal permeabilities of Pennsylvanian rocks in the province are very low, and this sequence of rock is essentially a very effective aquitard. Recharge from precipitation to the underlying Mississippian-age rocks through the Pennsylvanian is very low. The low permeability of the Pennsylvanian units is reflected by the flow characteristics of certain streams in southwestern Missouri. Streams flowing across the Pennsylvanian-age strata and then across Mississippian-age strata in southeastern Barton and northwestern Jasper counties do not gain flow while flowing on the Pennsylvanian rocks because the units have too low of permeabilities to yield appreciable groundwater. However, when the streams flow across the Mississippian rocks there is an immediate increase in flow, which shows groundwater discharging from the Springfield Plateau aquifer into the streams. Also, groundwater-level observation wells in the western margin of the Springfield Plateau that are cased through the Pennsylvanian strata and open to the Springfield Plateau aquifer show little or no response to local precipitation.

Although the Pennsylvanian rock is not considered an aquifer in the practical sense, shallow wells may encounter small amounts of groundwater in the Pennsylvanian. Yields are generally less than 5 gpm, and the water quality is typically poor due to excessive sulfate, total dissolved solids and iron.

GROUNDWATER CONTAMINATION POTENTIAL

The Springfield Plateau groundwater province has a moderate to high potential or susceptibility for groundwater contamination. Where Mississippian-age limestones directly underlie the surface, especially where karst features allow rapid introduction of water into the subsurface, the Springfield Plateau aquifer is especially vulnerable. However, because shallow- and intermediate-depth groundwater circulation is vertically restricted by

aquitards, the Ozark aquifer is less prone to contamination here than it is in the Salem Plateau groundwater province. Site evaluation guidelines for proposed waste systems and landfills should be kept stringent. It is also evident that large-scale use of pesticides could threaten groundwater quality in this area unless care is taken. The deeper aquifer units are at less risk, but the shallower zones are widely used for domestic water supplies and should be protected.

In the western part of the province where the Mississippian strata are overlain by low-permeability Pennsylvanian-age rocks, there is a very low potential for contamination of the deeper aquifers, and less potential for contamination of the Springfield Plateau aquifer. These areas would require less stringent engineering criteria for waste disposal facilities, and are not as likely to be affected by man's activities.

Although the Ozark and St. Francois aquifers in the Springfield Plateau are not highly prone to contamination, water-quality degradation can still occur in them. Unplugged abandoned wells that penetrate these aquifers can allow contaminants introduced at the surface to directly enter the deeper aquifer zones. Such an event occurred in the city of Republic in Greene County. The city of Republic well #1 is 1,000 ft deep and contains 300 ft of pressure-grouted casing set through the Northview Formation. The well is open to the Jefferson City and Cotter dolomites, Roubidoux Formation, and the upper half of the Gascon-

ade Dolomite. In 1982, sampling of this well under the National Synthetic Organic Chemical Survey revealed the presence of the solvent 1, 1, 2, trichloroethylene (TCE). Subsequent work showed the source of the TCE to be an abandoned circuit board manufacturing facility about 700 ft from the city well. The building housing the circuit board company burned in 1979. Extensive TCE contamination was found in the soils surrounding the building foundation. Excavation revealed a 540-ft deep abandoned well in the basement of the destroyed building. The well contained only 14 ft of casing, and samples showed water from it contained from 44,000 to 68,000 ug/L of TCE. The abandoned well allowed TCE to enter both the Springfield Plateau and Ozark aquifers as well as a fracture zone in the shallow limestone bedrock. Pumping city well #1 caused the contaminant plume to migrate the 700 ft distance between the city well and the contaminated abandoned well (figure 39).

A remediation project underway at the Republic site will eventually remove most of the TCE from the aquifers. However, the remediation could take more than 20 years, and will cost several million dollars. Obviously, the proper abandonment of any unused well should be a priority for any landowner. Proper well abandonment is required by law. Also, it is far less expensive to plug an abandoned well than to remove contaminants introduced into groundwater because of it.

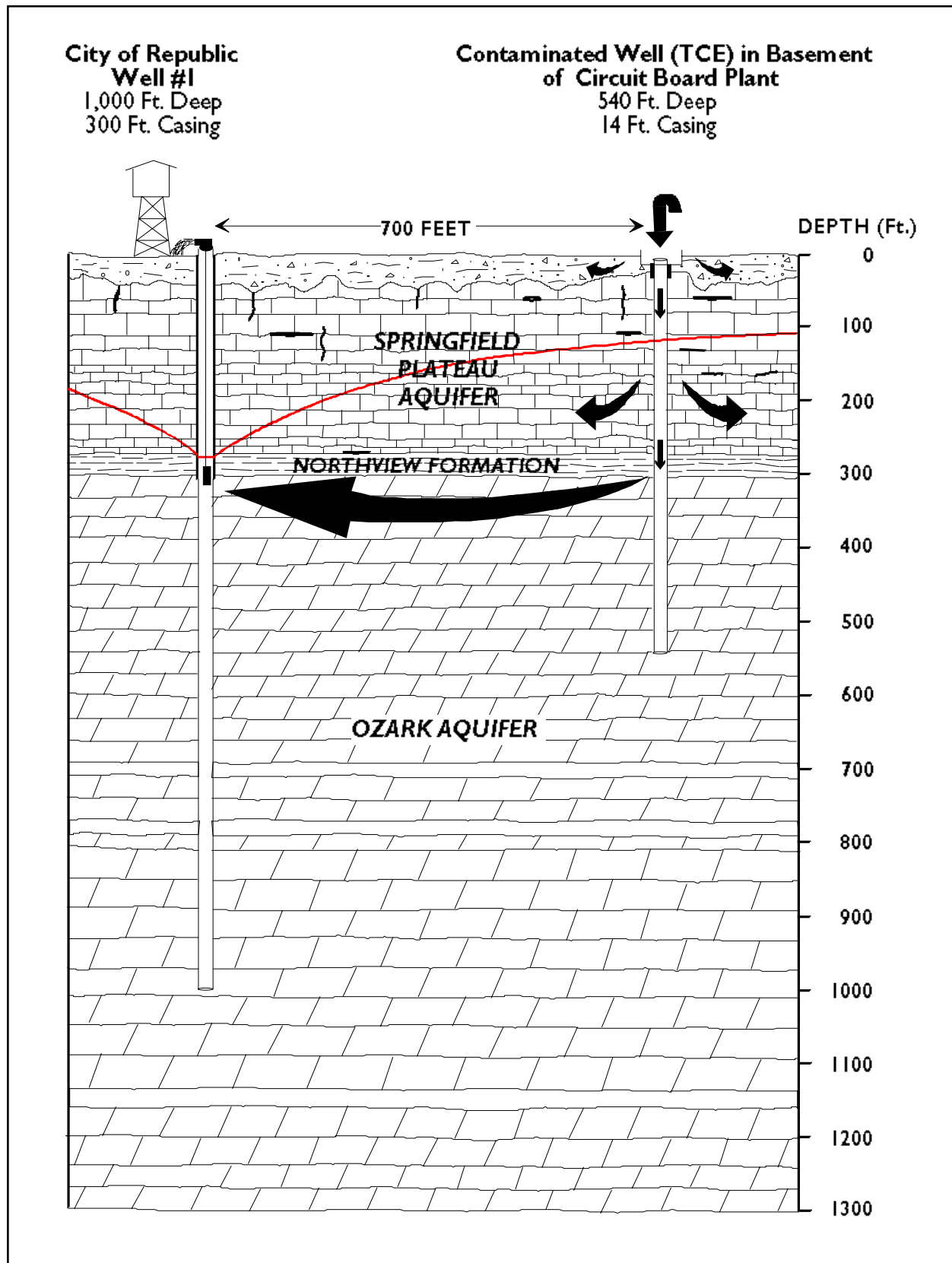


Figure 39. Cross-section at Republic showing contaminant paths and aquifers.

SOUTHEASTERN LOWLANDS GROUNDWATER PROVINCE (BOOTHEEL)

INTRODUCTION

The Bootheel region of Missouri, also known as the Southeastern Lowlands or Mississippi Embayment, is an area of approximately 3,916 square miles located in the extreme southeastern part of the state. This area includes all of Scott, Stoddard, Mississippi, New Madrid, Pemiscot and Dunklin counties, much of Butler County, and small parts of Ripley, Bollinger, Wayne and Cape Girardeau counties (figure 40).

The Southeastern Lowlands is the northern part of a much larger physiographic feature known as the Mississippi Embayment or the Mississippi Alluvial Plain. This feature is essentially contiguous with the Coastal Plain, which stretches across southeastern Texas eastward to include Florida, and northward up the east coast to include Long Island, New York.

Most of the Southeastern Lowlands is a nearly flat, alluvial plain. The fertile alluvial soils, coupled with a warm, moist climate, has helped the Bootheel to become the most productive agricultural region in Missouri. The mostly flat terrain is interrupted by a line of low hills that traverse the region from northeast to southwest, extending from northern Scott County into the northeast corner of Arkansas. This line of dissected hills, including Hickory Ridge, the Benton Hills, and Crowleys Ridge, are erosional or faulted remnants of a once more extensive upland surface that escaped the total destruction of erosion that leveled the rest of the Southeastern Lowland. Although suitable for some agricultural

activities, Hickory Ridge, the Benton Hills and Crowleys Ridge are not as well suited for large-scale row-cropping operations such as those found elsewhere in the Bootheel.

When explorers and settlers first arrived in the Southeastern Lowlands, the area was poorly drained and mostly consisted of swamp-land. There were relatively dry, elevated areas where farming could be practiced, but much of the region was under water or had very wet soil conditions much of the year. Drainage projects began around 1910 to improve surface drainage in the Bootheel. The Southeastern Lowlands had much more water to contend with than that supplied by rainfall. Runoff from sizeable parts of the St. Francois Mountains and Salem Plateau discharged into the Bootheel from the Castor, Whitewater, Black and St. Francis rivers. The Headwaters Diversion Channel was constructed along the northern part of the alluvial plain to route water from the Castor and Whitewater rivers directly into the Mississippi River just south of Cape Girardeau. In the 1940s, two large reservoirs were constructed on the Black (Clearwater Lake) and St. Francis (Wappapello Lake) rivers to control the volume of water entering the lowlands from those drainages. Levees and a series of north-south drainage channels were constructed to drain away excess surface water, lower the water table a few feet, and protect against overbank flooding.

The Southeastern Lowlands is the wettest part of Missouri. Though it receives from about 44 to 47 inches of precipitation during

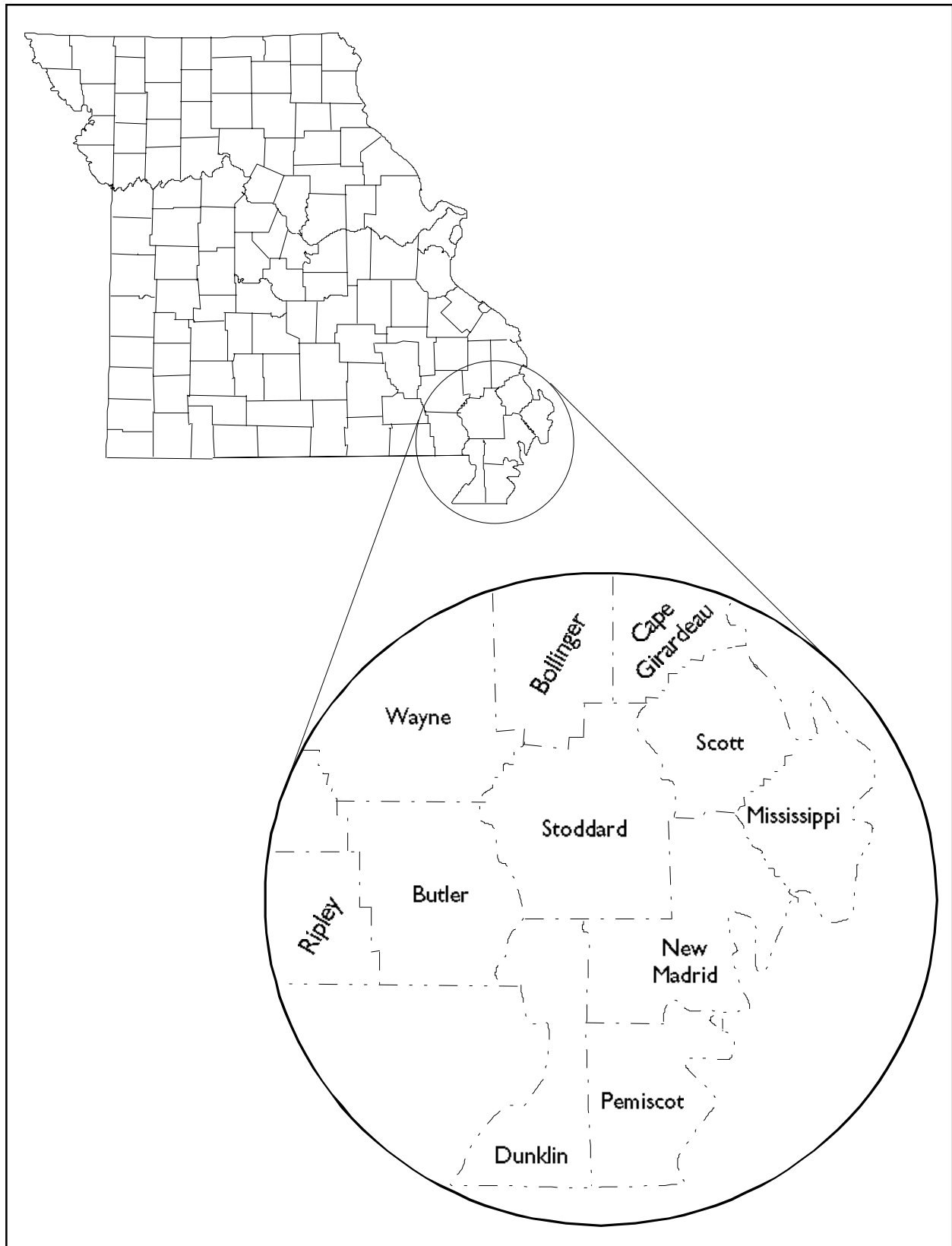


Figure 40. Map of Southeastern Lowlands groundwater province.

an average year, rainfall does not always occur when growing crops need the moisture. Many years ago, farmers discovered that crop production could be greatly enhanced in this area by using supplemental irrigation. The presence of large quantities of both groundwater and surface water became almost as important to the agricultural development of the area as the fertile soils and long growing season. As a result of this fortuitous combination of natural resources, the area has become the most heavily irrigated, and the most productive farmland in the state.

Although the Bootheel occupies only 5.7% of the state, it contains about 15 percent of the usable groundwater. Groundwater storage estimates show that the aquifers underlying the Southeastern Lowlands, combined, contain about 75.7 trillion gallons, or about 232 million acre-ft of water in storage, enough to cover an area the size of the Southeastern Lowlands with about 93 ft of water.

GEOLOGY

The Southeastern Lowlands are part of the larger Mississippi Embayment. The Missouri part of the lowlands is bounded on the north and west by the bedrock formations cropping out along the Ozark Escarpment, on the east by the Mississippi River, and on the south by the Arkansas-Missouri state line. Much of the area is underlain by Quaternary-age alluvial sediments deposited by the ancestral and modern Mississippi and Ohio river systems on top of older Tertiary, Cretaceous, and Paleozoic strata. Figure 41 is a map of the Southeastern Lowlands area showing the physiographic features mentioned above. A generalized stratigraphic description shown in table 12 displays the succession, character, thickness, extent, and hydrology of the sediments. For a more complete description of the geomorphology, and geologic history of the Bootheel, the reader is referred to Luckey (1985).

Much of the change in geologic characteristics between the Salem Plateau and the Southeastern Lowlands is due to geologic structure. The Mississippi Embayment area is considered the most structurally active and

complex area in the state. It is beyond the scope of this report to present a detailed description of the structural geology of this area, but some discussion is necessary to understand the present day geologic and hydrologic conditions.

The Mississippi Embayment is an area of extreme structural downwarping. Structural deformation began in the region as long ago as early Paleozoic time, but the northeast-trending structural trough of today began forming about 100 million years ago during the Late Cretaceous period. At that time, the area was underlain by Ordovician-age and older sedimentary rocks. Shallow seas transgressed over the area as the trough was formed and deepened. As subsidence occurred, Cretaceous and later Tertiary marine sediments were deposited in this trough. Depositional environments changed with time and with location. Coarser sediments, such as sands and gravels, were deposited in along the margins of the sea in shallow conditions, while limestones and shales were deposited in deeper parts of the trough. At the end of the Eocene, about 40 million years ago, seas regressed from the area, and it has since remained above sea level (Luckey, 1985).

Structural subsidence along the trough in Missouri is greatest in the extreme southeastern corner of the state. A structural contour map by Grohskopf (1955) shows about 2,900 feet of structural relief between the top of the Paleozoic rocks in southeastern Pemiscot County to the same horizon along the Ozark Escarpment. Figure 42 is a north-south geologic cross-section through the Southeastern Lowlands that shows the general dip of the strata.

Cretaceous and Tertiary sediments deposited in the Bootheel are thickest in the deeper parts of the trough, and thin toward the margins of the embayment.

PALEOZOIC STRATA (UNDIFFERENTIATED)

A distinction has been made between the unconsolidated, younger sediments of the Mesozoic and Cenozoic, and the underlying consolidated Paleozoic-age bedrock formations. In the southern and southeastern part of

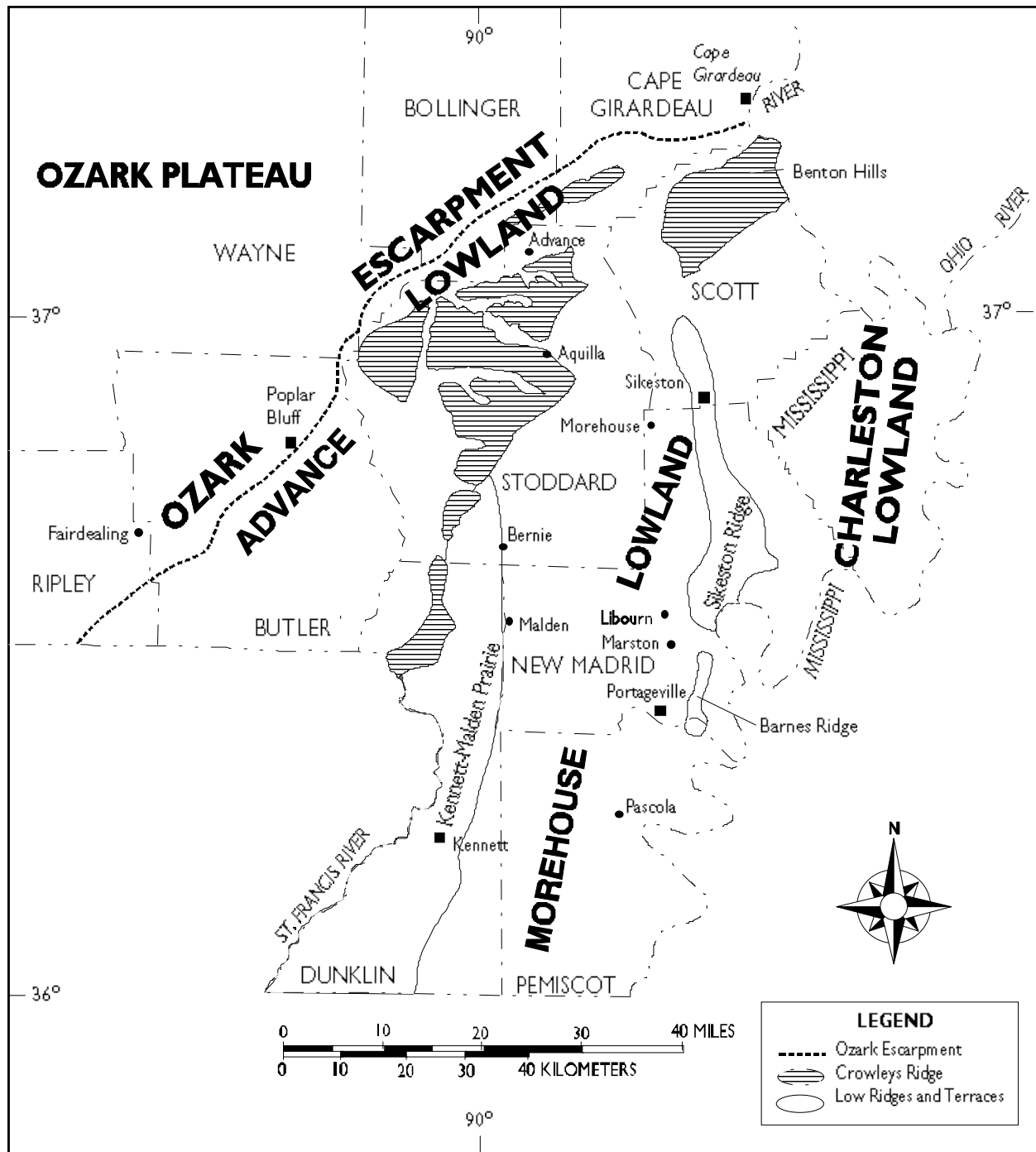


Figure 41. Physiographic map of the Southeastern Lowlands (from Luckey, 1985).

the Bootheel, the bedrock formations are too deeply buried or are not hydrologically significant in terms of yield or water quality to be of interest for this study. The exception to this is the area between Crowleys Ridge and the Ozark Escarpment. The Paleozoic rocks directly underlie the alluvium in much of this

area and are considered usable aquifers. South of about Puxico between Crowleys Ridge and the Ozark Escarpment, the Roubidoux Formation underlies the recent alluvial materials and forms the bedrock surface. Between Puxico and Delta, Jefferson City and Cotter dolomites underlie the alluvium. From Delta to the Missis-

Era	System	Group	Formation	Maximum thickness expected (feet)	Extent	Lithologic character	Hydrologic character
Cenozoic	Quaternary		Alluvium	250	Underlies entire lowland area except Crowley's Ridge	Gravel, sand, silt, & clay.	Chief aquifer in the area. May yield 3,000 gpm to wells in some localities.
			Loess	35	Covers Crowley's Ridge, Benton Hills, & uplands.	Tan to brown silt. May contain some clay.	Occurs above the water table.
	Tertiary		Terrace Gravel	60		Gravel, cobbles, some clay.	
			Wilcox	1,400	Crops out on Crowley's Ridge & Benton Hills. Underlies all of area south and east of line from Campbell to Charter Oak to Sikeston to Lusk.	Sand, some clay. Contains thin beds of lignite.	A major aquifer used chiefly for municipal supply. Known to yield 1,500 gpm in favorable localities. May contain at least two aquifers with separate potentiometric surface.
		Midway	Porters Creek Clay	650	Crops out on Crowley's Ridge & Benton Hills. Underlies all of area south and east of line from Neelyville to Bloomfield to Commerce.	Clay, light gray when dry, but dark gray when wet.	Does not yield significant quantities of water to wells. Acts as barriers to groundwater movement.
			Clayton Formation	30		Calcareous, glauconitic sand and clay to fossiliferous limestone.	
Mesozoic	Cretaceous		Owl Creek Formation	100	Crops out on Crowley's Ridge and Benton Hills. Underlies entire area except within about ten miles of Ozarks.	Bluish-gray to brown sandy clay.	Generally impedes the flow of groundwater.
			McNairy Formation (Ripley Sand)	600 (combined thickness)		Sand, sandy clay, and clay. Nonmarine at outcrop, but marine in deep part of the embayment.	A significant aquifer widely used for municipal supplies. High heads make this aquifer attractive but excessive mineralization and high temperatures limit its use in some areas.
			Pre-McNairy Cretaceous Beds		Present only in deeper parts of the embayment	Sand, chalk, marl, clay, and limestone.	
Paleozoic				>2,680	Crops out on Crowley's Ridge, Hickory Ridge, & Benton Hills. Underlies entire area.	Limestone, sandstone, and dolomite	Used for municipal supplies close to the Ozarks. Would probably yield large amounts of water in other areas but this water may be highly mineralized in some areas.

(The stratigraphic nomenclature used in this report is that of the Missouri Division of Geology and Land Survey)

Table 12. Generalized stratigraphic section of sediments in the Southeastern Lowlands groundwater province (modified from Luckey, 1985).

Mississippi River, younger Ordovician rock, including the Kimmswick and Dutchtown formations, underlie the alluvium. The hydrologic characteristics of the shallow Paleozoic units between the Ozark Escarpment and Crowley's Ridge are much the same as immediately to the northwest in the Salem Plateau. East of Crowley's Ridge, the Paleozoic units are generally too deep to be considered practical for water

supply, and probably contain water that is too highly mineralized to be considered potable.

CRETACEOUS SYSTEM

McNairy Formation

The Cretaceous-age McNairy Formation is the oldest stratigraphic unit that has hydrologic significance in the area southeast of Crowley's Ridge. Pre-McNairy Cretaceous beds

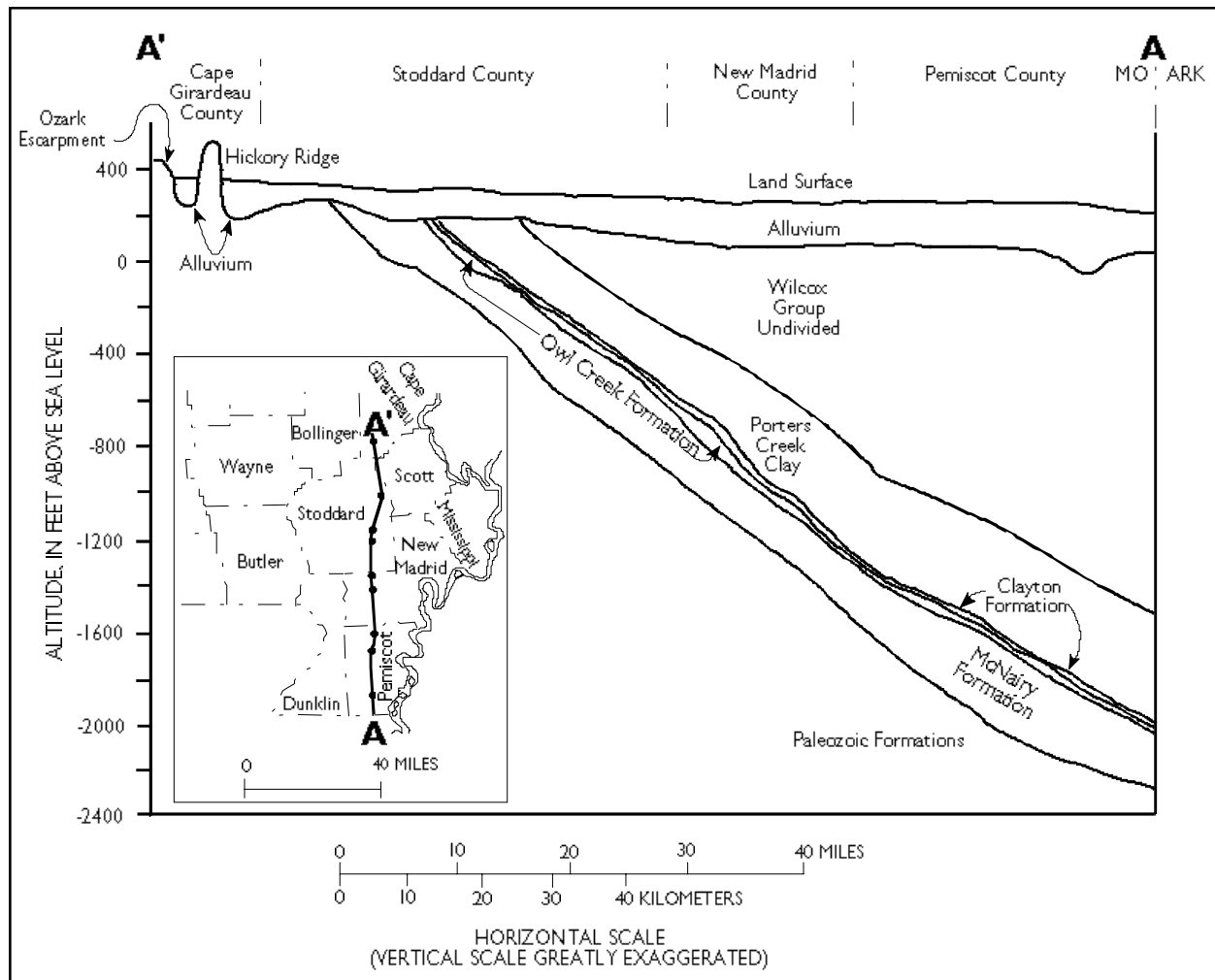


Figure 42. North-south geologic cross-section of the Southeastern Lowlands (modified from Luckey, 1985.)

underlie the McNairy in the deeper parts of the trough. These materials consist of sand, chalk, marl, clay and limestone, and are not considered significant aquifers.

The McNairy crops out on Crowleys Ridge and unconformably overlies the Paleozoic units throughout the area to the east and south. It is present throughout the Southeastern Lowlands except within about 10 miles of the Ozark Escarpment. The McNairy consists of sand, sandy clay and clay, and ranges from less than 100 ft thick in its outcrop area to more than 600 ft thick in the extreme southern part of the Bootheel. The unit is considered non-marine in the outcrop area, but is a marine deposit through the deeper part of the Embayment (Luckey, 1985).

Owl Creek Formation

The Owl Creek, the youngest Cretaceous-age unit in the area, overlies the McNairy Formation. It consists of up to 100 ft of brown, glauconitic sandy clay where the full thickness of the formation is present, but in some areas much of the Owl Creek was removed by erosion before deposition resumed in the Tertiary.

TERTIARY SYSTEM

Midway Group: Clayton Formation and Porters Creek Clay

Sedimentary rock of the Midway Group overlies the Owl Creek Formation throughout much of the Southeastern Lowlands. The lowermost unit is the Clayton Formation,

which consists of up to about 30 ft of various sediments including calcareous, glauconitic sand and clay, and limestone. The unit is generally more clastic near the boundaries of the Embayment, and more calcareous in the deeper parts of the trough (Grohskopf, 1955). The Clayton is overlain by a much thicker clay unit called the Porters Creek Clay. This unit is up to about 650 ft thick, and consists of dark-gray clay. The Porters Creek is present throughout the Southeastern Lowlands south and east of Crowleys Ridge.

Wilcox Group (undifferentiated)

The Wilcox Group overlies the Porters Creek, and consists of up to about 1,400 ft of sand with some clay and thin beds of lignite. The unit crops out along the southeastern side of Crowleys Ridge and the Benton Hills, and underlies all of the Southeastern Lowlands south and east of a line extending from Campbell to Charter Oak to Sikeston to Lusk (Luckey, 1985). It is thinnest along its outcrop belt, and thickest in the deepest parts of the trough. Quaternary alluvium overlies the Wilcox throughout much of the area.

Terrace Gravels

Up to about 60 ft of terrace gravels overlie the Wilcox in some areas. Where these gravels are not overlain by alluvium, they are easy to distinguish in the subsurface. However, where alluvium overlies them, they are difficult to distinguish from the basal gravels of the alluvium.

QUATERNARY SYSTEM

Alluvium

The youngest stratigraphic unit that has hydrologic significance is the Quaternary-age alluvium. The alluvium overlies older stratigraphic units throughout the entire Southeastern Lowlands except for Crowleys Ridge, Hickory Ridge, Benton Hills, and a few other low ridges where Tertiary-age sands crop out. The alluvium consists mostly of sand and gravel with lesser amounts of clay and silt at the surface. Thickness of the alluvium varies with location. It is generally thinnest west of

Crowleys Ridge where it ranges from zero to about 200 ft thick. East of Crowleys Ridge the alluvium is somewhat thicker, and is locally more than 250 ft thick in extreme southern Dunklin and Pemiscot counties and southeastern Mississippi County.

The alluvium was deposited by the actions of the Mississippi and Ohio Rivers, and to a much lesser extent, the actions of the St. Francis, Black, Castor and Whitewater rivers. The actions of these rivers also are responsible for much of the physiographic character of the lowlands. According to Magill (1968), as presented by Luckey (1985), the Mississippi River originally turned southwest just south of Cape Girardeau, and flowed through the area between the Ozark Escarpment and Crowleys Ridge called the Advance Lowlands. At the same time, the Ohio River was following a channel through the southern tip of Illinois, north of its present course, and along the southeast side of Crowleys Ridge. The Ohio, which was probably a few feet lower than the Mississippi, captured the Mississippi through stream piracy and the Mississippi River eroded the gap between Crowleys Ridge and Benton Hills. Later, a similar stream piracy between an Ohio River tributary and the Mississippi river east of Benton Hills moved the confluence of the two rivers upstream to near its present position.

HYDROGEOLOGY

There are several separate and distinct aquifers in the Southeastern Lowlands that have different hydrogeologic characteristics. Two of these consist of Paleozoic consolidated rock units, while the other three are mostly comprised of younger unconsolidated sediments. In ascending order they are the St. Francois aquifer, Ozark aquifer, McNairy (Ripley Sand) aquifer, Wilcox aquifer, and the alluvial aquifer. There are also several confining units that greatly limit the vertical movement of groundwater between the aquifers.

PALEOZOIC BEDROCK AQUIFERS

Paleozoic (Ordovician-age and older) bedrock underlies essentially all of the South-

eastern Lowlands. In some locations between Crowleys Ridge and the Ozark Escarpment, the alluvium is directly underlain by Ordovician bedrock. Most of these units are dolomites with lesser quantities of sandstone. Between Crowleys Ridge and the Ozark Escarpment, the Ozark aquifer is commonly used for private domestic water supply and, to a much lesser extent, for public water supply. Although the alluvium in this area is shallower and has large quantities of water available, it generally contains high levels of dissolved iron that requires treatment before it is usable for some purposes.

Little is known about the St. Francois aquifer in this area. It is thought to contain potable water between the Ozark Escarpment and Crowleys Ridge, but there is little information to substantiate this.

The Paleozoic bedrock aquifers are also present at greater depths throughout the entire Southeastern Lowlands area. However, east and south of Crowleys Ridge the depth to the bedrock becomes excessive, and there is ample water available from numerous shallower aquifer zones so the Paleozoic bedrock aquifers are not used in this area. There is a gradual deterioration in bedrock aquifer water-quality from northwest towards the southeast across the Bootheel. The Ozark aquifer dips or tilts towards the southeast, and as it dips, it also thickens. The further downdip the individual aquifers zones become, the more highly mineralized their water becomes. The relatively meager data currently available for bedrock aquifers in the area south and east of Crowleys Ridge indicates that these zones commonly contain water that is too highly mineralized for most uses. A well drilled to test for the possibility of oil in Mississippi County reached a depth of 4,900 feet, and produced water that contained almost 67,000 mg/L total dissolved solids concentration (Luckey and Fuller, 1980). Water produced from these same zones farther to the north in Scott County is of much better quality, and meets public drinking water standards.

Yields of wells penetrating the Paleozoic bedrock aquifers in the Southeastern Low-

lands are similar to those of wells penetrating the same zones in the Salem Plateau area to the northeast; yields vary greatly with location, depth, and zones open to the aquifer. Yields of a few gallons per minute are generally available to private domestic wells penetrating the uppermost part of the bedrock. Deeper wells in favorable locations can yield several hundred gallons per minute.

Data are currently inadequate to fully characterize the hydraulic and water-quality characteristics of the Paleozoic bedrock in the Southeastern Lowlands. Available information indicates that west of the eastern margin of Crowleys Ridge, the Paleozoic bedrock aquifer contains fresh water. This consists of an area of about 1,400 square miles. The estimated volume of usable groundwater in storage in this area in the St. Francois aquifer is 2.59 trillion gallons, or about 7.9 million acre-ft. The Ozark aquifer is estimated to contain about 7.88 trillion gallons, or about 24.2 million acre-ft.

McNairy Aquifer

The McNairy Formation, locally referred to as the Ripley Sand by many area water well drillers and residents, underlies about 3,328 square miles, or nearly 85 percent of the Southeastern Lowlands. This aquifer is widely used for municipal water mainly because of two factors. First, the McNairy is under considerable artesian head in some of the area, and in places the potentiometric surface is several feet above ground level. The high static water levels in the wells penetrating the McNairy greatly reduce pumping costs. More significantly, away from the outcrop belt along Crowleys Ridge, the McNairy yields very soft water that contains little dissolved calcium, magnesium and iron. Water from the shallower Wilcox Group and the alluvium almost always requires treatment for iron and manganese removal. Water from the McNairy typically does not. The depths of wells producing from the McNairy vary greatly from less than 200 ft in the northern and western parts of the Southeastern Lowlands, to more than 2,000 ft in southern Dunklin and Pemiscot counties.

Yields of wells penetrating the McNairy vary somewhat, but generally range between 150 and 750 gpm. Yields are lowest on and along Crowleys Ridge where the unit is relatively thin, and also in other places where the McNairy may be thick but where clay interbeds greatly decrease the total thickness of clean, permeable sand. Several aquifer tests performed on wells penetrating the McNairy generally show transmissivities ranging from 9,000 to 16,000 gpd/ft (1,200 to 2,140 ft²/day), and storage coefficients of about 1×10^{-4} . Storage coefficients are generally higher, about 1×10^{-3} , in the outcrop area of the unit along Crowleys Ridge. The direction of groundwater movement in the McNairy in Missouri appears to be generally to the southeast.

The quality of water from the McNairy varies with location and proximity to recharge sources. The McNairy likely receives recharge from three sources. The most obvious source is precipitation falling on the unit where it crops out on Crowleys Ridge, or where surface stream-flow is directly across it. There is probably considerable recharge to the McNairy from the overlying alluvium west of Crowleys Ridge where the unit is directly overlain by alluvial materials. In both of these areas, water from the McNairy contains less sodium, more iron, calcium and magnesium, and has a higher carbonate hardness than in areas to the south and east. There is probably very little recharge to the McNairy from either the alluvium or Wilcox Group east and south of Crowleys Ridge. The thick Porters Creek Clay has very low hydraulic conductivity, and combined with the Clayton and Owl Creek formations form a very effective aquiclude separating groundwater in the Wilcox Group from that in the McNairy. There is evidence that the McNairy receives some recharge from the deeper Paleozoic bedrock aquifers. Water quality in the McNairy is poorest in a roughly circular area covering eastern Stoddard, southern Scott, southwestern Mississippi, and much of New Madrid counties (figure 43). Here, total dissolved solids and chloride concentrations in the McNairy generally exceed public drinking water standards. The reason

for the poor water quality in this area is not entirely clear, but may be due to faulting, which has allowed salinewater from deeper Paleozoic units to move upward into the McNairy (Luckey, 1985).

Although the McNairy underlies an area containing about 3,328 square miles, the area of the aquifer containing water with less than 250 mg/L chloride is about 2,701 square miles. The volume of potable water stored in the Ripley is estimated to be about 12 trillion gallons, or about 37 million acre-ft.

WILCOX AQUIFER

The Wilcox Group is the thickest of the unconsolidated aquifers in the Southeastern Lowlands, ranging from zero along the southeastern side of Crowleys Ridge to more than 1,250 ft in southeastern Pemiscot County. It underlies an area of about 2,346 square miles, or about 60 percent of the Southeastern Lowlands. Although all of the unit is water-saturated, it does not possess uniform water-yielding characteristics. It is mostly sand, but clay and lignite beds in the formation reduce hydraulic conductivity in parts of the unit. Most high-yield wells drilled into the Wilcox target a thick, permeable sand zone near the base of the unit where there are few clay beds. Generally, the lowermost 250 to 400 ft of the formation contains the greatest quantity of clean sand.

Properly constructed wells penetrating the Wilcox Group generally yield from less than 200 gpm where the unit is thin near its outcrop belt, to as much as 1,700 gpm where the unit is much thicker. The quality of water from the Wilcox is less desirable than that of the McNairy. Water from the Wilcox Group is typically a calcium-bicarbonate or calcium-magnesium-bicarbonate type. Total dissolved solids, sulfate and chloride typically meet public drinking water standards. The only constituents that present problems to public water suppliers are iron and manganese. Both of these metals are typically present above public drinking water standards. Iron levels above 0.3 mg/L and manganese levels above 0.05 mg/L can cause staining of laundry and

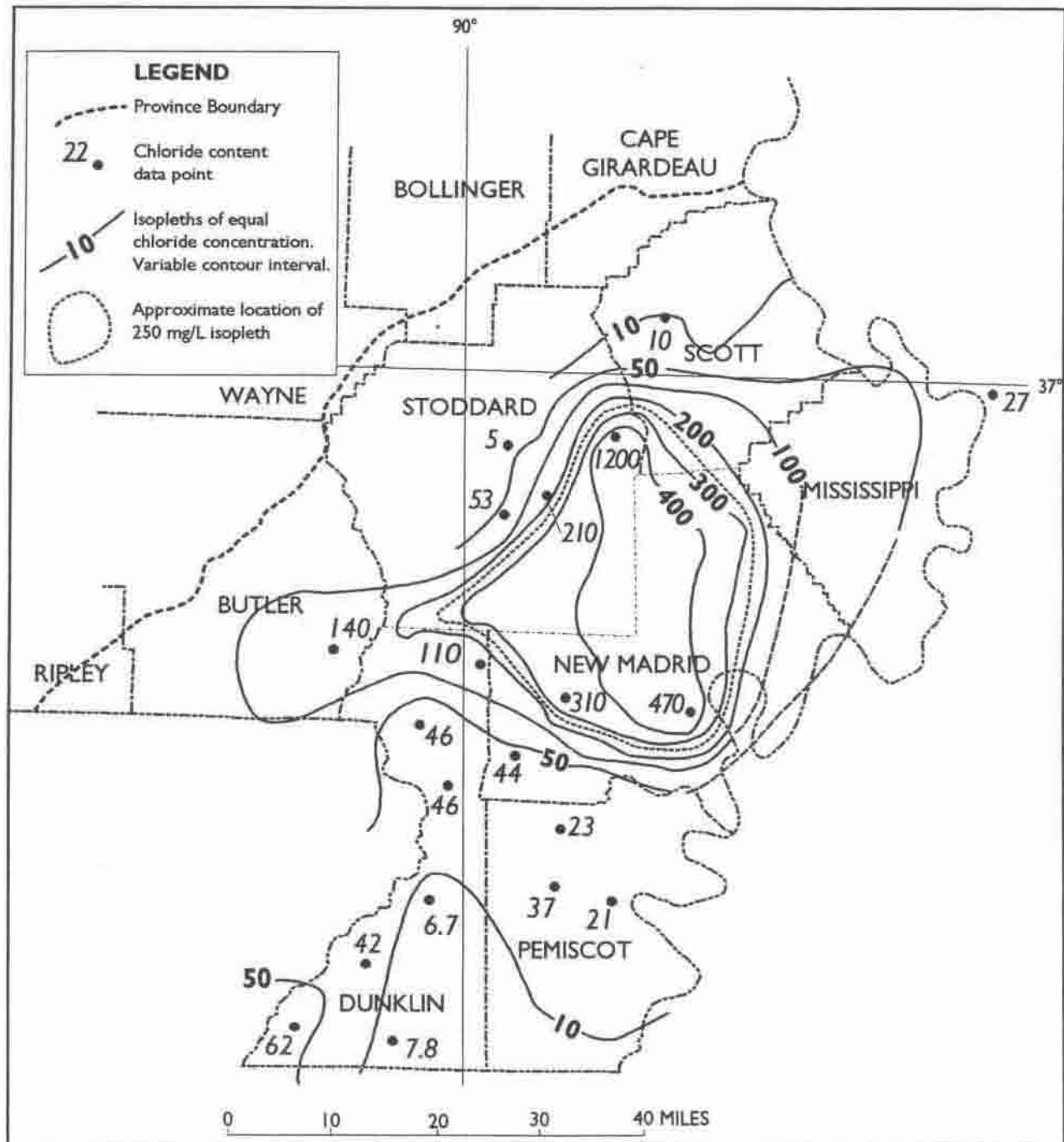


Figure 43. Chloride content in the McNairy aquifer, Southeastern Lowlands (from Brahana and Mesko, 1988).

plumbing fixtures. Water from the Wilcox commonly contains from 0.3 mg/L to about 4 mg/L. Manganese is generally between 0.03 mg/L and 0.3 mg/L. Although these metals are higher than desirable in groundwater from the Wilcox, they are generally much lower than levels found in the shallower alluvium.

The Wilcox aquifer receives recharge from downward movement of water from the overlying alluvium, particularly in the area immediately southeast of Crowleys Ridge where the thicker, more permeable sands of the Wilcox are directly overlain by alluvium. Based on water-level measurements from wells pen-

etrating the lower Wilcox, the direction of groundwater movement in the unit is generally to the south (Luckey, 1985).

The Wilcox likely contains a greater volume of fresh water than any other aquifer in southeastern Missouri. It is estimated to contain about 32 trillion gallons, or about 98 million acre-ft.

SOUTHEAST LOWLANDS ALLUVIAL AQUIFER

Without question, the most widely used aquifer in the Southeastern Lowlands is the alluvial aquifer. The alluvium underlies about 92 percent of the Southeastern Lowlands, an area of approximately 3,677 square miles (figure 44). Its thickness ranges from 0 to as much as 300 feet, with the thinner areas adjacent to the Ozark Escarpment along the northwest boundary, and adjacent to Crowleys Ridge and Benton Hills. The alluvium consists of unconsolidated sand, gravel, silt and clay, deposited mostly by the ancestral Mississippi and Ohio river systems (Luckey, 1985). The only places in the Southeastern Lowlands where the alluvium is absent is on Crowleys Ridge, Benton Hills, and other similar positive features that are well above floodplain level.

Groundwater is stored and transmitted in the alluvium through intergranular pore space. The gradient of the water table is generally to the south and quite low, about 1 ft/mi. Water-table elevation in the northern end of the Embayment is about 330 ft msl, while it is about 90 ft lower at the Arkansas border at the southern tip of the Bootheel. West of Crowleys Ridge, groundwater in the alluvium generally moves toward the south, and toward the Black and St. Francis rivers. East of Crowleys Ridge, the overall direction of alluvial groundwater movement is also to the south, but toward either the Little River drainage ditch system, or farther east toward the Mississippi River channel (figure 45).

Yields of wells drilled into the alluvium depend on several factors including the saturated thickness of the alluvium, the diameter of the well and length of well screen, and the hydraulic conductivity of the alluvial materials. Properly constructed high-yield wells pen-

etrating the alluvium rarely yield less than 500 gpm, and can yield as much as 3,000 gpm. Specific capacities typically range from 35 to 150 gpm/ft of drawdown. Aquifer tests of the alluvial aquifer show that it has a very high transmissivity. East and south of Crowleys Ridge, transmissivity values are generally between 240,000 and 400,000 gpd/ft (32,000 and 54,000 ft²/day). Storage coefficients calculated from short-term tests of about 24 hours or less are generally between 1×10^{-4} and 2×10^{-3} . During longer term pump tests, the storage coefficients would likely increase several orders of magnitude, and would more closely resemble the effective porosity of the alluvial materials less the specific retention.

Aquifer tests performed on alluvial wells west of Crowleys Ridge show that the alluvium in that area is generally less permeable than to the east and south of Crowleys Ridge. Transmissivities in this area can be between about 112,000 gpd/ft and 350,000 gpd/ft (15,000 and 47,000 ft²/day). Storage coefficients are similar to those east of Crowleys Ridge. The alluvium west of Crowleys Ridge is thought to be more closely associated with the St. Francis, Black and ancestral Mississippi rivers, while that to the east is more closely associated with the Ohio and modern-day Mississippi rivers.

Water levels in the alluvium fluctuate in response to several factors, all related to aquifer recharge or aquifer discharge. The alluvial aquifer receives most of its recharge from precipitation. Recharge is generally greatest where the surficial materials are very sandy and less where they contain a higher percentage of silt or clay. There is also appreciable recharge in the aquifer near the Mississippi River during high river stages. Overall, however, most of the recharge is due to infiltration from precipitation.

Discharge from the alluvial aquifer is both from natural and artificial means. Natural discharge is generally from water movement from the alluvium into the Mississippi, St. Francis and Black rivers, the Little Blue River drainage ditches, and the Headwaters Diver-

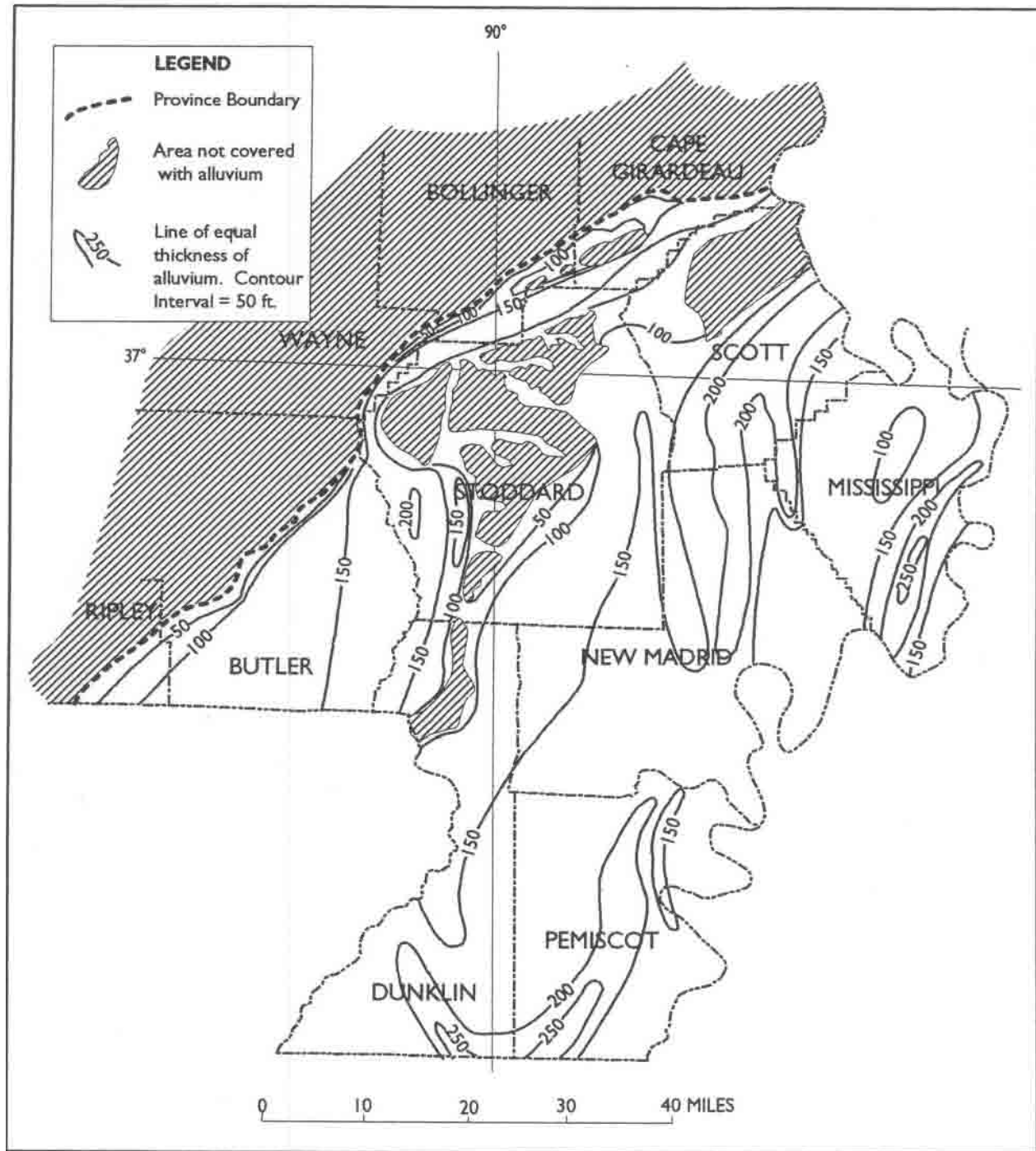


Figure 44. Thickness and extent of the Southeastern Lowlands alluvial aquifer (from Luckey, 1985).

sion Channel. However, potentiometric data shows that the St. Francis River along the west edge of the Bootheel may actually provide some recharge to the alluvium (Luckey, 1985). Where permeable sands of the McNairy and Wilcox subcrop beneath the alluvium, there is

downward movement of alluvial water into them. Also, there is groundwater movement laterally through the alluvial aquifer in Missouri into northern Arkansas.

During spring, summer and early fall months there is a seasonal lowering of water

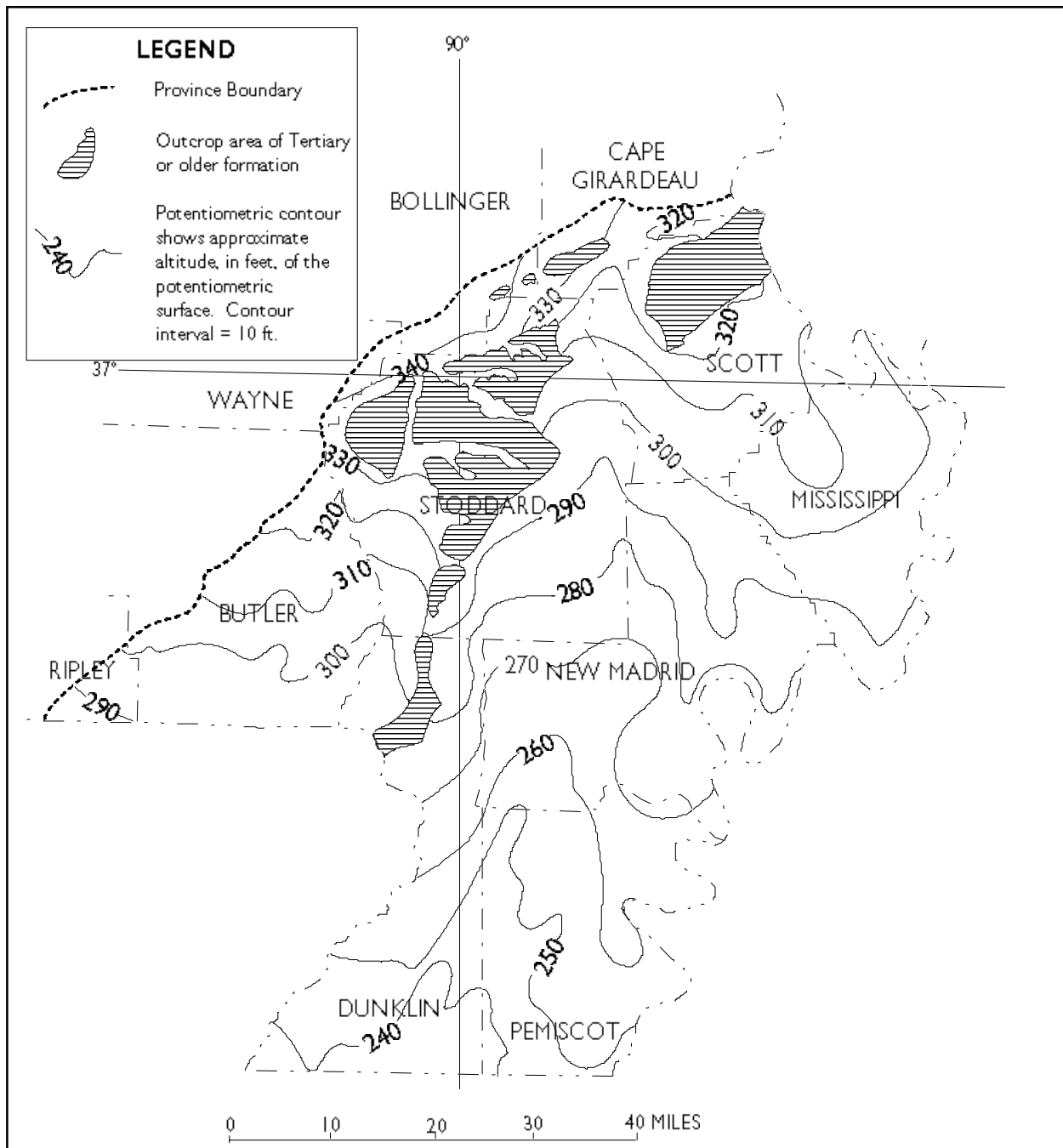


Figure 45. Generalized potentiometric surface of the alluvial aquifer in southeastern Missouri during the spring of 1976 (from Luckey, 1985).

levels within the alluvium that is partly in response to increased evapotranspiration. In areas where the water table is shallow, deep-rooted plants can use groundwater and will cause some lowering of water levels. Also, because of increased evaporation during

warm weather, there is less recharge from the precipitation that does occur.

Under natural conditions, the lowest groundwater levels in the alluvium are usually in the late fall, and levels recover slowly throughout the winter, with the highest or

shallowest groundwater levels occurring in the spring when recharge from precipitation is highest. The artificial removal of groundwater from the alluvium by high-yield wells however, generally masks the effects of natural groundwater fluctuations.

In terms of the volume of water used and the number of wells that produce from it, the alluvial aquifer in the Southeastern Lowlands is by far the most extensively used aquifer in the Southeastern Lowlands. Private domestic wells in rural areas that produce from the alluvium are typically only a few feet deep to a few tens of feet deep. Most of these low-yield wells are driven sand points or jetted wells. Rotary drilling equipment is not widely used for domestic-type wells in the Southeastern Lowlands. These wells use water from the shallow part of the alluvium. This water generally contains less iron and manganese than the deeper alluvial materials. However, the upper part of the alluvium is typically more fine-grained than the lower part, and thus has a significantly lower hydraulic conductivity. Some public water supply wells that produce from the alluvium are also able to take advantage of the slightly better water quality in the shallower part of the alluvium.

The greatest usage of groundwater in the Southeastern Lowlands is for agricultural irrigation, and the most widely used aquifer for irrigation is the alluvial aquifer. Luckey and Fuller (1980) inventoried 3,091 irrigation wells in the Southeastern Lowlands, which they estimated to be about 75 percent of the total number of irrigation wells. Prior to passage of the Water Well Drillers Act in 1985, the Division of Geology and Land Survey received information for only a small percentage of the total number of wells drilled. However, after August 1987, drillers were required to file well completion forms on most types of wells including irrigation wells. Between January 1, 1987, and September 30, 1996, the Division of Geology and Land Survey received well records for 2,225 irrigation wells that were drilled during that period in Butler, Dunklin, Mississippi, New Madrid, Pemiscot, Scott and Stoddard counties. Nearly all of these wells

probably produce from the alluvial aquifer. From this information, about 230 irrigation wells are drilled each year in the Southeastern Lowlands. Part of these are replacement wells for existing irrigation systems, while others are drilled to supply new irrigation systems. Based on the above there could currently be as many as 7,800 irrigation wells in the Southeastern Lowlands.

Long-term groundwater level monitoring throughout the Bootheel indicates that despite increased water use, there has been little or no net decline of water levels in the alluvial aquifer since the first water-level monitoring wells were installed in 1956. During the irrigation season, groundwater levels in many areas will decline several feet in response to pumping, but will recover during nonpumping intervals to their prepumping levels. In some instances, nearby private water supplies have been adversely impacted by irrigation pumpage, and have not recovered rapidly due to seasonal low water levels during the growing season, and continued irrigation pumpage.

Figure 46 shows the locations of groundwater-level observation wells operated in the Southeastern Lowlands by DGLS, and the years of record available for each well. Figure 47 shows long-term water-level information collected at several observation wells in the Southeastern Lowlands. All of the graphs show that despite the very large quantities of water used for agricultural irrigation, water levels in the alluvial aquifer have not changed appreciably since the first observation wells were installed in 1956.

Recharge to the alluvium throughout the Bootheel through precipitation, surface-water inflow and groundwater inflow is approximately 9.9 million acre-feet a year. Outflow from the system is through surface water leaving the area, evapotranspiration and groundwater outflow. Outflow includes water that leaves the area at the state line, discharge into the Mississippi River and recharge to the deeper aquifer units. Groundwater pumpage by irrigation and municipal/industrial users totals about 115,000 acre-feet a year (Luckey, 1985).

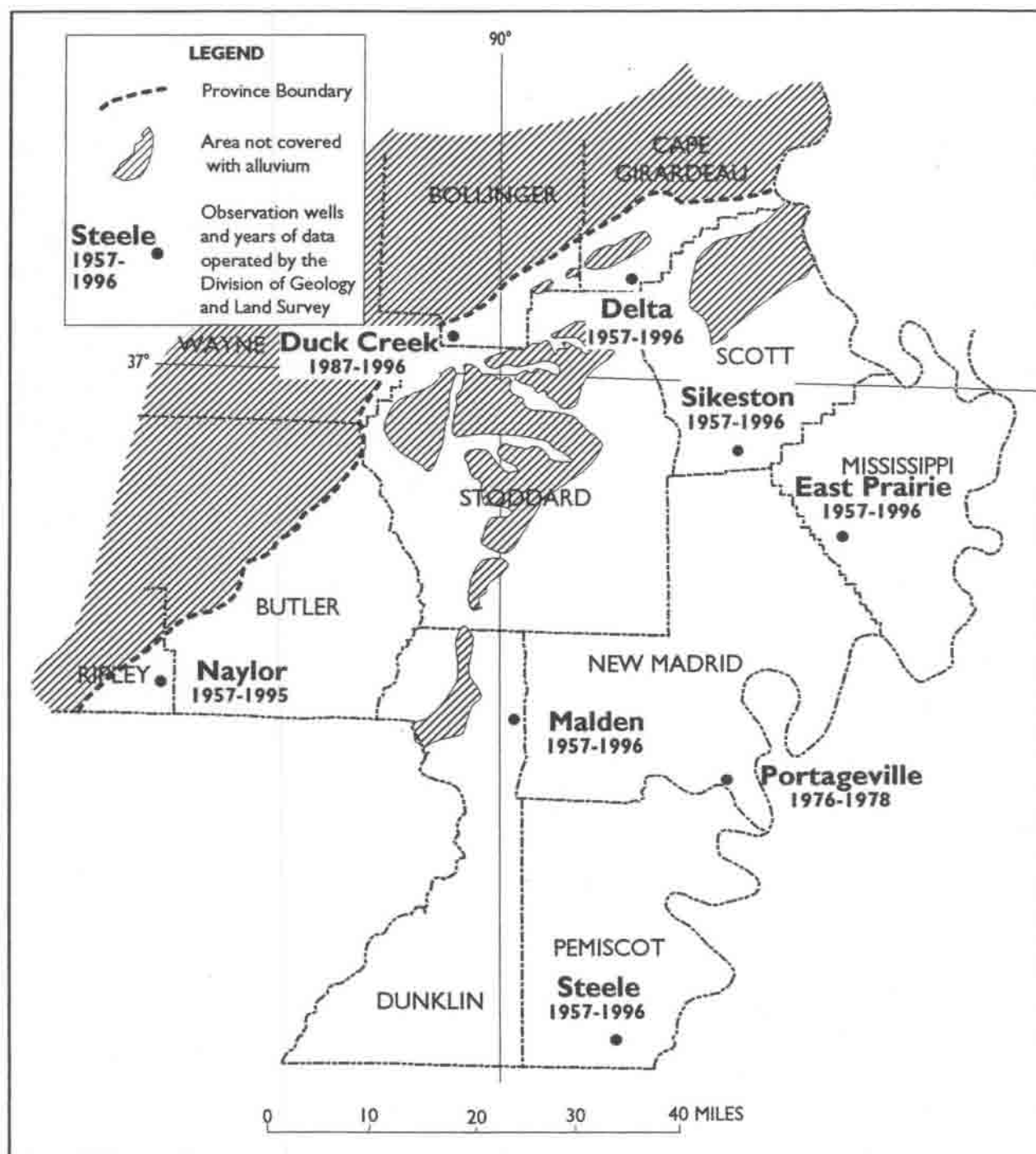


Figure 46. Locations of Southeastern lowlands observation wells operated by the Division of Geology and Land Survey.

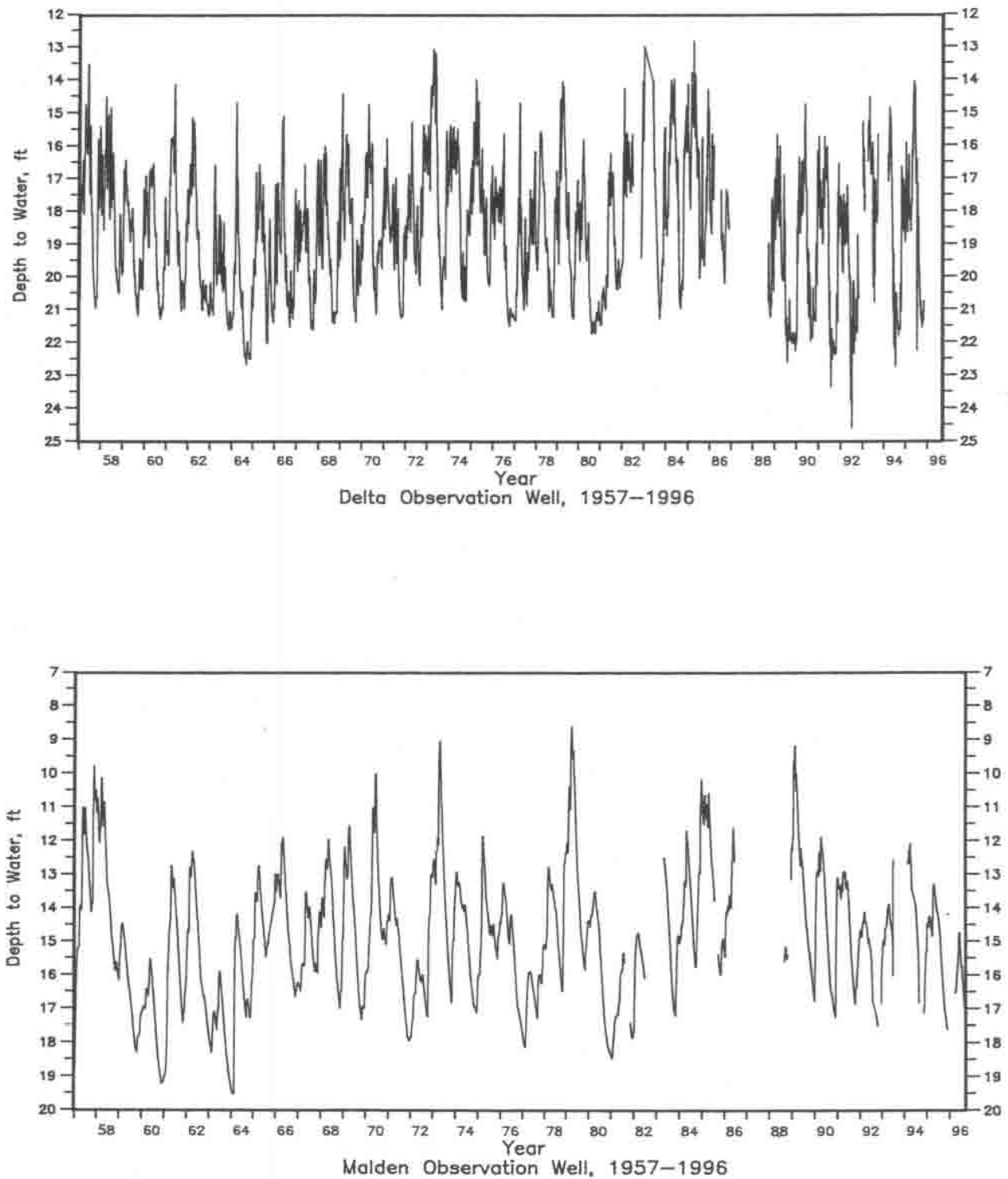
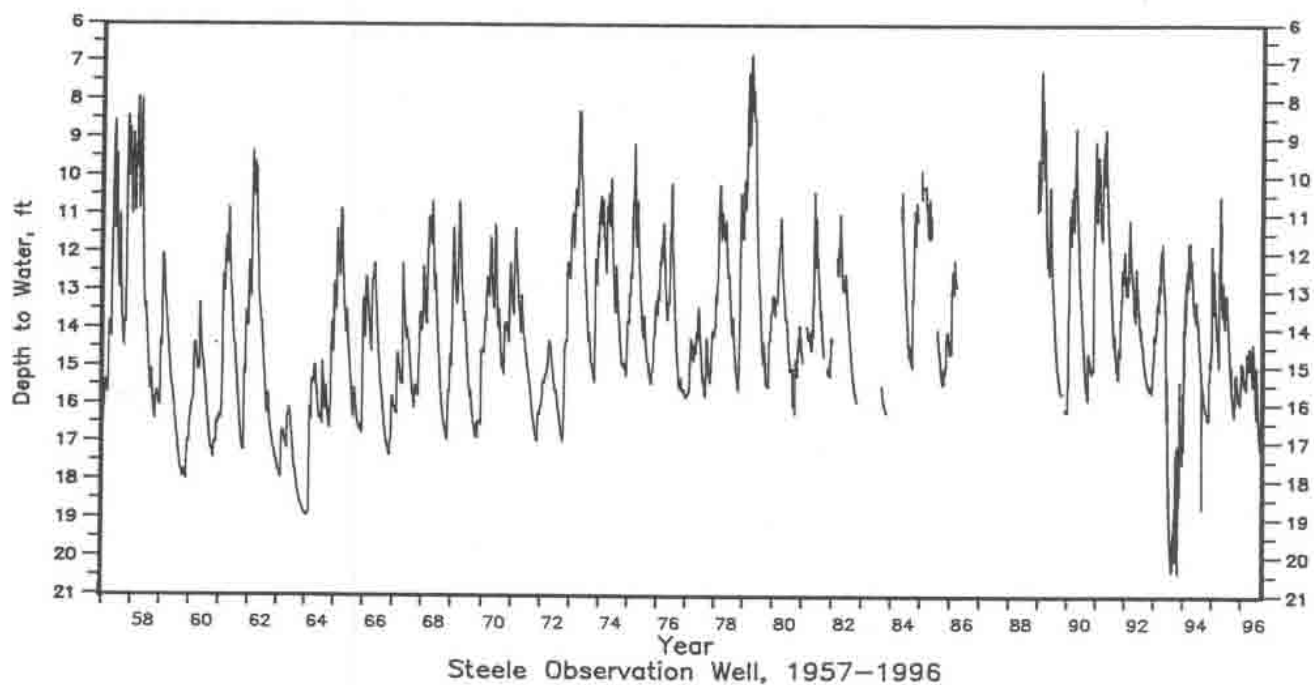
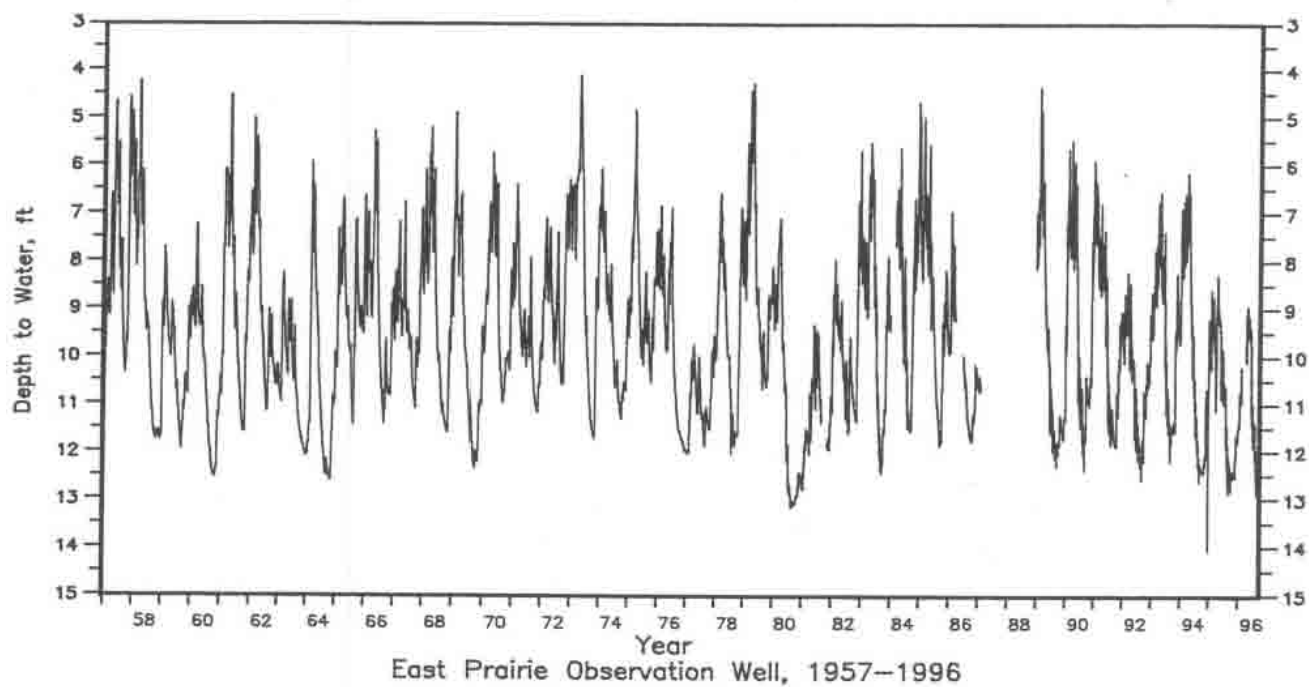


Figure 47. Long-term water-level changes at selected observation wells in the Southeastern Lowlands.

Figure 47 continued.



Luckey also assumed that about 60 million acre-feet of groundwater is stored in the alluvium at any one time, which represents six years of total inflow, 10 years of evapotranspiration, and 500 years of pumpage.

Storage estimates made during this study indicate that the average volume of water stored in the alluvial aquifer varies with season, but is typically about 21 trillion gallons, or about 65 million acre-ft.

WELL INTERFERENCE

If several adjacent alluvial irrigation wells are pumping concurrently, the drawdown cones can merge, and cover a fairly large geographic area (figure 48). If there are nearby, shallow driven or jetted domestic wells, lowering of water levels just a few feet can mean the difference between pumping water

and having a temporarily dry well. This is especially true with domestic wells equipped with centrifugal pumps that can produce water only from relatively shallow depths. The pumping equipment used in the larger, high-yield wells allows for the pumping of water from greater depths than does the centrifugal pump wells commonly used in shallow wells.

During dry summer months when irrigation is occurring, the cone of influence produced by irrigation wells will lower water levels significantly in addition to the natural, seasonal water-level declines that occur during the drier times of the year. Where the soil is sandy and more permeable, some water will flow back into the aquifer, but only that portion which escapes evapotranspiration. In the more clayey soils, runoff from the fields into drainage-ways precludes much recharge from taking place.

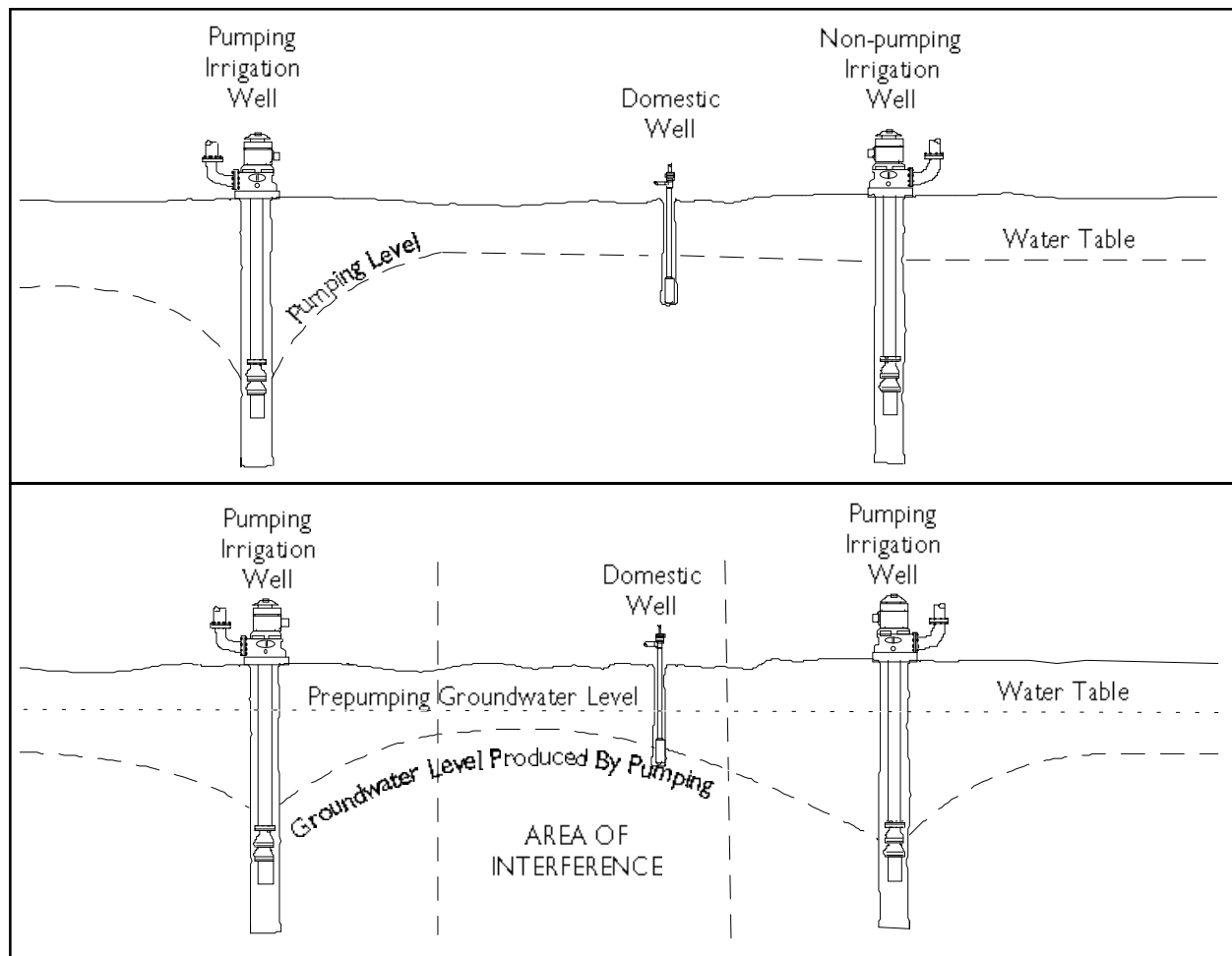


Figure 48. Generalized areas of interference from multiple pumping irrigation wells.

Well interference is best avoided by placing high-yield irrigation wells as far as possible from shallower, domestic wells. Still, problems are likely to occur, especially in areas where groundwater production is high, and wells of substantially different depths produce from the same aquifer. Historically, such disputes have been dealt with in civil courts.

GROUNDWATER CONTAMINATION POTENTIAL

The potential for groundwater contamination varies greatly in this region. All of the aquifers are prone to contamination in their outcrop areas. Sand units in the Wilcox Group are subject to contamination throughout the southeastern part of Crowleys Ridge where they are close to the surface and not protected by significant overlying aquitards. Where the McNairy Formation is overlain by the Midway Group, it is well protected from vertical contamination because of the low permeability of the Porters Creek Clay. Contamination potential of the Paleozoic bedrock aquifers from contaminant sources on Crowleys Ridge is fairly low. The Paleozoic units crop out over only a small area on Crowleys Ridge; the more productive units are quite deep, with substantial artesian-head pressures.

The complexity of the geology and water resources of the Crowleys Ridge-Benton Hills area makes careful siting of waste treatment and disposal facilities most important. Contaminant movement through sands in the Wilcox and McNairy aquifers would be relatively slow, but natural flushing of them would also be quite slow. Thus, contaminants introduced into these units would be very difficult to remove and clean-up costs would be quite high.

Because of its widespread occurrence and shallow position, the alluvial aquifer is probably the one most likely to be affected by contaminants. Since the Southeastern Lowlands are primarily an agricultural area, it may seem logical that agricultural chemicals such as pesticides, herbicides and fertilizers would

be the most common types of contaminants. However, water-quality studies in the area have failed to discover significant evidence that this type of contamination is presently a problem, even in areas underlain by permeable, sandy soils. Sites that have the highest potential for this type of contamination are where agri-chemicals are handled such as at airports serving crop-spraying operations, and agricultural chemical distribution outlets. There are some sites of these types where groundwater contamination has been documented. Fortunately, such problems are relatively few.

Even though contamination due to the use of agricultural chemicals does not seem to be a major problem at the present time, it would be ill advised to assume that the unrestricted use of fertilizers, pesticides and herbicides in the Bootheel will not cause problems if proper precautions are not taken. The risk is further increased if chemicals are applied immediately before heavy rainfall when they are more apt to be carried by runoff into drainage-ways, and subsequently infiltrate into the shallow groundwater system. The potential for groundwater contamination also increases when chemicals are applied near improperly constructed irrigation wells or in the presence of abandoned wells. A common practice in the Southeast Lowlands is to use irrigation water to spray agricultural chemicals onto crops. Chemigation, the application of agricultural chemicals by mixing them with irrigation water as it is being sprayed, allows chemicals to be applied while irrigation is taking place. However, if not practiced with extreme care, this practice can be a source of groundwater contamination. Check-valves or other backflow prevention devices must be used to prevent the accidental introduction of chemicals into the well bore.

Use of chemical fertilizers has, in many areas of the United States, significantly raised nitrate levels in groundwater aquifers. Application rates that are in excess of what crops need for optimum production are often the cause of problems in these areas. This type of practice is costly in two ways. First, the farmer

is paying for fertilizer that is not increasing crop yields. Second, the surplus nutrients can leach downward through the soil zone and into the saturated part of the alluvium. Over time, increased nutrients in the shallow aquifer zones can adversely affect private water supplies, and in some aquifer settings, also affect public water supplies.

Contamination that occurs as a result of by-products produced by industries, pipelines, railroad accidents, municipal waste products, highway spills and a myriad of other sources, is a real possibility, and is known to have occurred at some locations in the Bootheel. For example, an unlined lagoon constructed on a sand ridge several miles north of Sikeston in Scott County allowed waste fluids generated by a metal plating operation to leak into the shallow alluvial aquifer. Thankfully, groundwater movement in the alluvium is generally slow, so these types of contamination events do not typically affect large areas. However, as the economy of the area continues to expand, even localized events can have a cumulative effect and could cause more widespread economic and social problems.

The avenues for contaminant transport in the Bootheel are numerous. The most common one is simply the vertical movement of contaminants through the soil, and into the shallow groundwater system. This is a particular problem in areas underlain by sandy, permeable soils. In areas underlain by more clayey, less permeable soils, the clay-sized particles have enough absorbent capabilities to trap fairly large amounts of the contaminants, and for this reason, large areas of the

Bootheel are less vulnerable to this type of contamination. Figure 49 is a generalized soil map of the Bootheel showing areas underlain by tighter, clayey soils. Figure 50 shows the general appearance of a contaminant plume in alluvial sediments. This plume is based on a contaminant that is very soluble in water, and whose density is approximately the same as water. Insoluble contaminants that are more or less dense than water may generate contaminant plumes that differ greatly than the one shown.

Abandoned, unplugged wells present another avenue for contaminants to enter the groundwater system. They are essentially conduits for surface pollutants to enter the system very rapidly. In some areas, drainage wells have been used to drain water from areas that remain wet for long periods of time. This practice should be avoided since it can also introduce agricultural chemicals into the subsurface.

It is a good practice to avoid the mixing of agricultural chemicals at or near wellheads. If precautions are not taken, chemicals can be accidentally siphoned from sprayer tanks when they are being filled. This can occur if the check valve in a pump fails, or a large opening develops in the pump pipe in the well.

Leakage of surface retention lagoons used for agricultural runoff, municipal waste or agricultural waste products such as feedlots and swine or poultry production, are locally a source of elevated nitrate concentrations. This type of contamination is probably not as widespread as other sources, but, as mentioned above, does contribute to the cumulative total for the area.

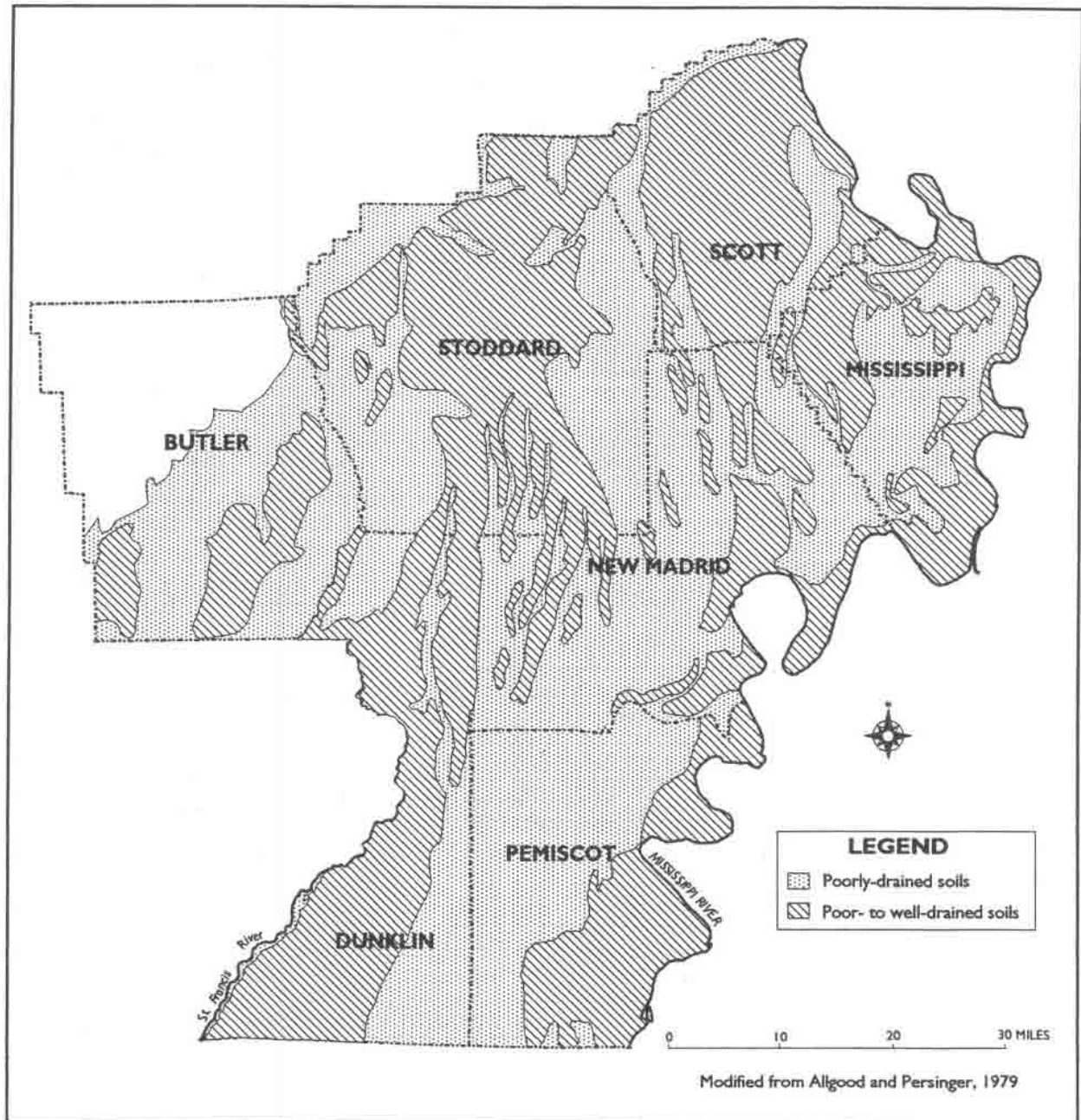


Figure 49. Generalized soil map of the Bootheel.

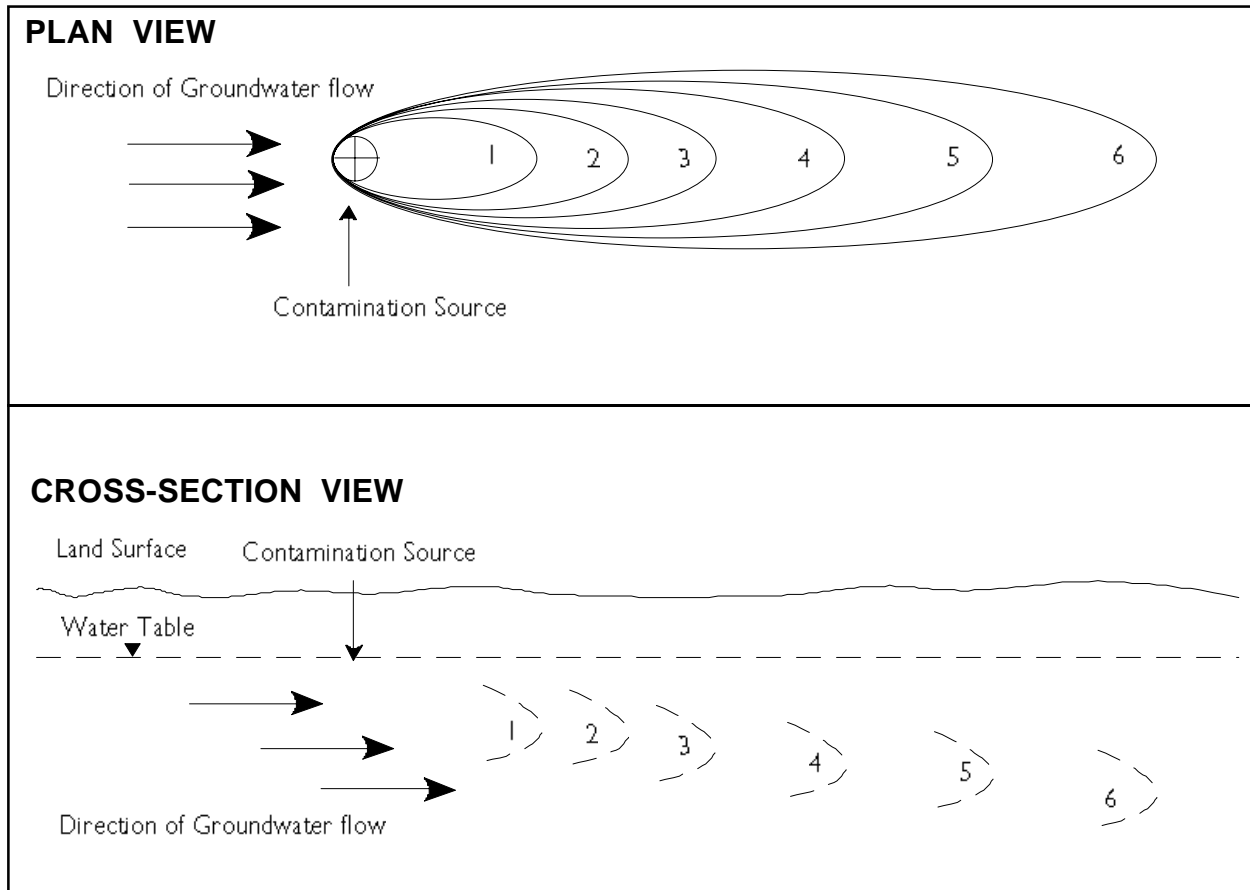


Figure 50. Plan view and cross-section of a hypothetical contaminant plume in an alluvial aquifer. Numbers indicate the limits of the plume at various times in its development.

MISSISSIPPI RIVER ALLUVIUM

INTRODUCTION

The alluvial aquifers beneath the floodplains of the Mississippi and Missouri rivers are some of Missouri's most valued water resources. These aquifers are capable of yielding from 500 to more than 2,000 gpm to properly designed and developed wells, and are widely used for municipal water supply and agricultural irrigation.

The Mississippi River forms most of the eastern border of Missouri, and its total length in Missouri is 485 miles. This includes approximately 123 miles where it borders the Bootheel. A comparison of geologic maps of Illinois and Missouri quickly shows that the Mississippi River tends to follow the bluff line on the Missouri side of the river. With the exception of the Southeastern Lowlands, discussed previously, there are only a few locations in eastern Missouri where there is a significant amount of Mississippi River alluvium. These occur in eastern Clark and extreme northeastern Lewis counties, eastern Marion County and extreme southeastern Lewis County, eastern Pike, Lincoln and St. Charles counties, a small area in eastern St. Louis County, a small area in eastern Ste. Genevieve County, and an area in northern Perry County (figure 51). The total surface area of Missouri that is underlain by Mississippi River alluvium, excluding the Bootheel, is approximately 440 square miles. With such localized and small geographic distribution, the alluvium of the Mississippi River is not considered a major water source in Missouri. However, locally it is a very significant resource.

Where present, the alluvium ranges in thickness from a featheredge near the valley walls to approximately 170 feet; it is typically thickest adjacent to the river. In all cases, the alluvium was deposited by the action of the river, meandering back and forth across its valley over a several thousand year period. The position of the channel is much different today than it was in the past. Today, most of the significant areal extent of Mississippi alluvium is on the Illinois side of the river. There have been times in the past, however, when the channel was much further to the east, and hundreds of additional square miles of alluvium was west of the river.

The alluvium is composed of fine to coarse sand, fine to medium gravel, silt and clay. Because of the manner in which it was deposited, the extreme variability of the alluvium from one location to another makes it difficult to locate optimum high-yielding well sites. In almost all instances, test drilling is needed to determine the most favorable locations where there is the greatest thicknesses of high-permeability sands and gravels.

Because of the limited aerial extent of the alluvium of the Mississippi River in Missouri, discussion will be by county, from the northernmost occurrence in Clark County, to the southernmost occurrence, in Perry County. The alluvium in the Southeastern Lowlands was discussed previously and will not be readdressed here.

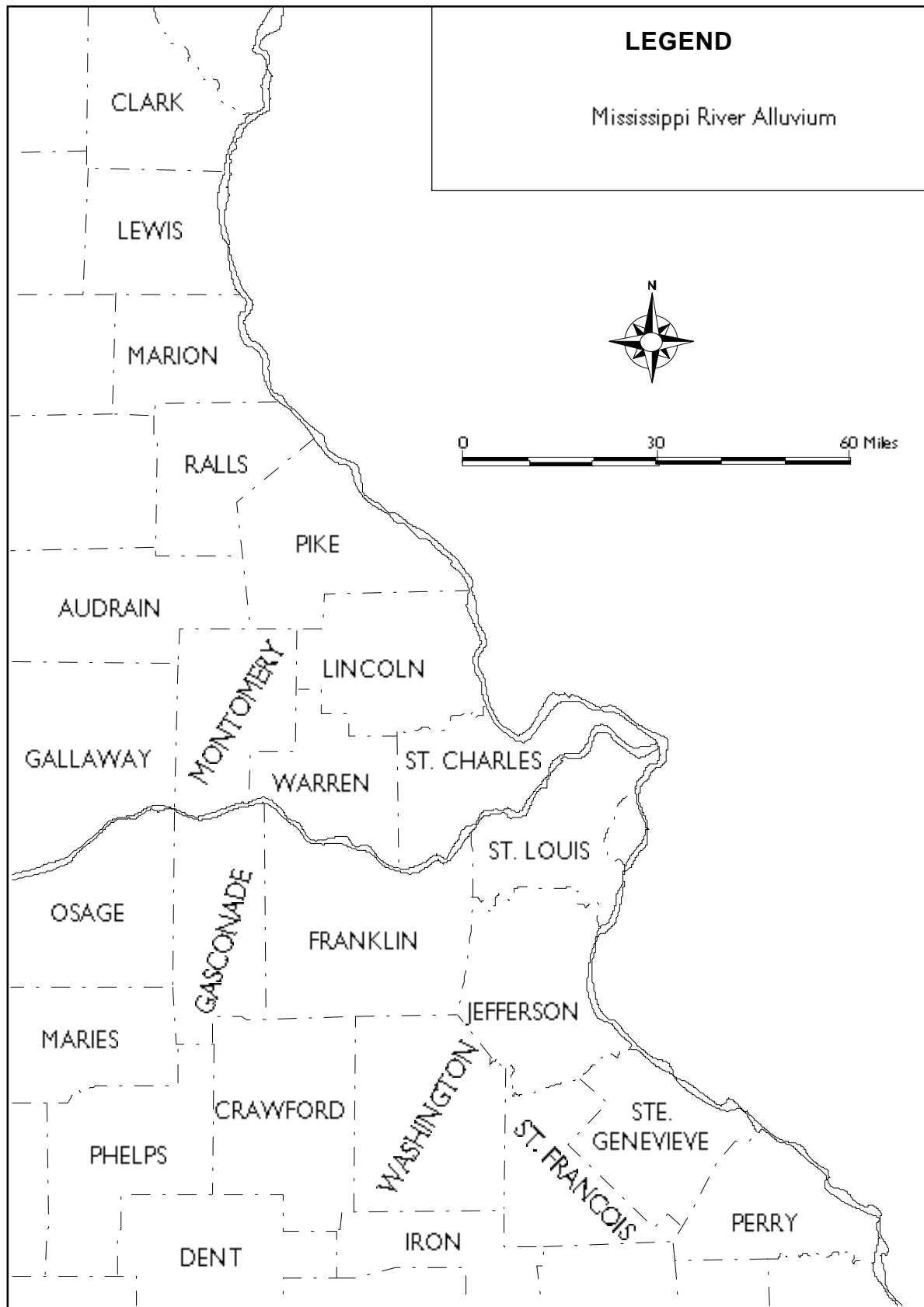


Figure 51. Distribution of Mississippi River alluvium in Missouri.

CLARK AND NORTHEASTERN LEWIS COUNTIES

A fairly large area of alluvium is found in eastern Clark County and extreme northeastern Lewis County, just south of the confluence of the Mississippi and Des Moines rivers. Alluvium here overlies an area of about 77 square miles. Prior to the deposition of the modern alluvium, and prior to the advance of the last continental ice sheets of the Pleistocene, the channel of the Des Moines River followed a much different path than does the modern river. The trend of this ancestral river was more southerly where it entered Missouri. It is not known if this drainage change was due to the effects of glacial ice diverting the flow to the south, and if the present day valley of the Des Moines is the preglacial route. However, there is a buried channel of the ancestral Des Moines River that underlies the alluvium of the Mississippi in Clark County. Figure 52 is a generalized map showing the possible configuration of this buried channel.

There are few wells that produce from the permeable zones in this buried channel. In 1971, the city of Kahoka in Clark County initiated an exploratory drilling program near the town of Wayland to find a source of municipal groundwater. This test drilling program delineated a small section of the channel, and one production well was drilled into it. As drilling progressed, the production well encountered 50 feet of shallow, modern alluvial materials, 55 feet of fine-grained glacial sediments, and finally 55 feet of preglacial, ancestral Des Moines River alluvium. During a controlled aquifer test, this well yielded 775 gpm, had a transmissivity of more than 33,000 gpd/ft (4,411 ft²/day), and had a storage coefficient of 0.08.

In 1974, the Division of Geology and Land Survey installed a water-level recorder on a well at Wayland that is open to the ancestral Des Moines River alluvial channel. Figure 53 is a groundwater-level hydrograph, showing water levels for the Wayland observation well. It was noted shortly after the water-level recorder was installed that local precipitation had very little, if any, affect on

groundwater levels. This is undoubtedly due to the poor vertical permeability between the preglacial valley deposits and the overlying alluvium of the Mississippi River. There are noticeable seasonal affects from spring through winter, but little or no response to individual rainfall events. Most of the water-level changes are due to pumpage of a nearby city of Kahoka well.

A few irrigation wells produce alluvial groundwater in this area. The average thickness of the alluvium here is only about 100 ft, somewhat less than in areas further to the south. There does seem to be a potential for increased use, however, since the average thickness of clean, permeable sand and gravel is large enough to yield 500 gpm or more to properly constructed wells.

As in other alluvial areas, the quality of the groundwater contained in the alluvium of this area is good, with the exception of fairly large concentrations of iron and manganese. However, production wells located near the present channel of the river should be able to induce recharge to the aquifer from the river, and thereby improve the quality of the production water from the well.

Storage estimates indicate that the Mississippi River alluvium in Clark County contains about 88 billion gallons of water in storage, or about 270,300 acre-ft. In northeastern Lewis County, the alluvium is estimated to contain another 20.2 billion gallons or 61,950 acre-ft. This is based on an assumed average saturated thickness of 80 ft, and a specific yield of from 0.08 to 0.11.

SOUTHEASTERN LEWIS AND MARION COUNTIES

Very little data are available for the 54-square-mile area underlain by Mississippi River alluvium in eastern Marion County and extreme southeastern Lewis County. However, as in Clark County, it is reasonable to assume that there is a sufficient thickness of permeable alluvial materials that can supply high yields to wells drilled in the alluvium. This is supported by data from two alluvial wells, drilled for industrial purposes in Sec. 3,

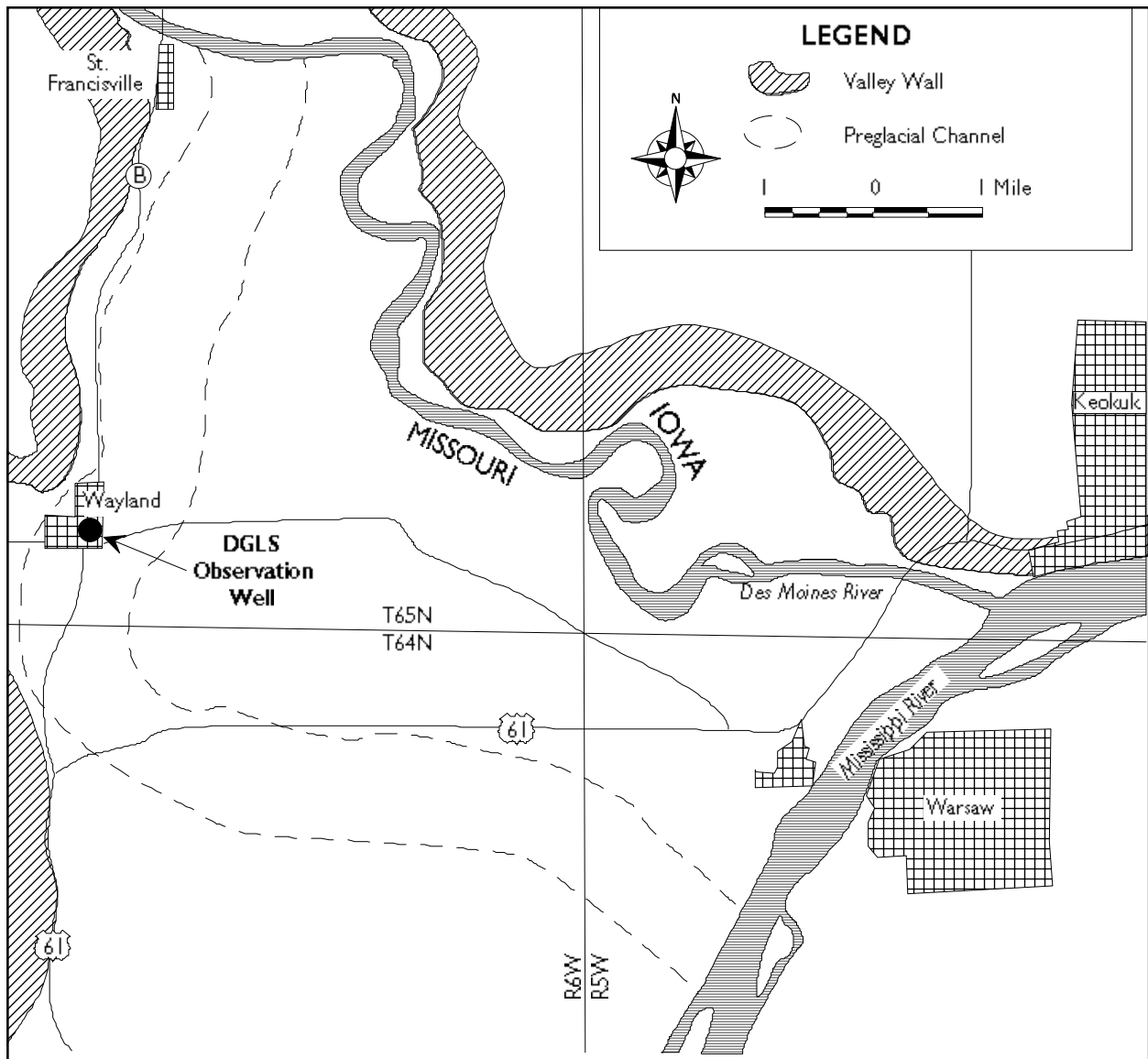


Figure 52. Possible configuration of preglacial Des Moines River channel in Clark County, Missouri.

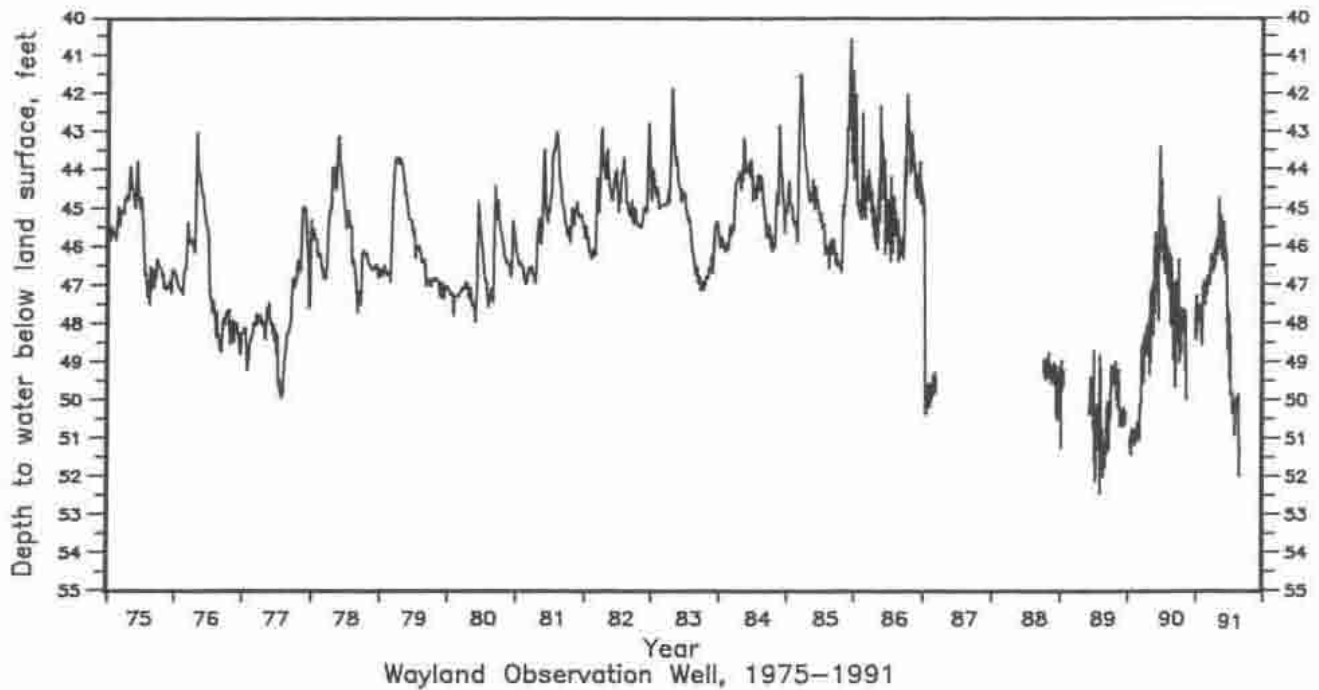


Figure 53. Groundwater-level hydrograph, Wayland observation well, Clark County.

T. 58 N., R. 5 W. These wells encountered 150 feet of alluvial material, and yielded 1,200 and 1,400 gpm. The Division of Geology and Land Survey has a groundwater-level recorder installed in an abandoned industrial well a short distance south of the aforementioned wells. Drilled in 1957 to a depth of 129 feet, this well had a yield of only 215 gpm, which was inadequate for its intended use. Instead of plugging the well, the owners donated it to the Missouri Geological Survey (now the Division of Geology and Land Survey) for its water-level measuring program.

This well shows water-level changes that reflect river stages. There is a delay time of about four days, between a rise in river stage,

and a rise in water levels in the observation well. This is not to say that water is entering the alluvial aquifer and moving to the well. Since in this type of alluvial setting groundwater gradients in the alluvium are towards the river and slightly downstream, it simply means that the steepness of the gradient has been lessened by the "damming effect" of higher stream levels, and that groundwater is temporarily stored in the aquifer, raising water levels until the river stage drops.

In southeastern Lewis County, the alluvium is estimated to contain about 23.9 billion gallons of water in storage, or about 73,200 acre-ft. In Marion County, another 157.7 billion gallons or 483,800 acre-ft are estimated to be stored in the alluvium.

PIKE, LINCOLN, ST. CHARLES AND ST. LOUIS COUNTIES

In eastern Pike County, at the mouth of the Salt River, is an area of about 18 square miles underlain by Mississippi River alluvium. Very little data exists for this small alluvial area. A much larger alluvial area begins farther downstream in Pike County. Extending from Clarksville in Pike County, to the confluence of the Missouri and Mississippi rivers in northeastern St. Louis County, is the longest continuous reach of Mississippi River alluvium in Missouri other than in the Boot-heel. This area contains a total of about 230 square miles of Mississippi River alluvium.

There are no data available in DGLS files for alluvial wells in Pike County, but data from wells in Lincoln County, T. 49 N., R. 2 E., show that the Mississippi River alluvium there has a good potential for both municipal and irrigation use. In 1957, the city of Winfield drilled an alluvial well that yielded 197 gpm. Although this yield may appear small, the well had only 1.9 feet of drawdown during pumping. The specific capacity of this well is in excess of 100 gpd/ft, and the aquifers transmissivity here is estimated to be about 150,000 gpd/ft (20,000 ft²/day). This well was developed in only 71 ft of alluvial material. A nearby irrigation well, drilled to a depth of 68 ft, yielded 1,570 gpm with a drawdown of 13.9 ft. Specific capacity for the well was 115 gpm/ft of drawdown, and from this transmissivity is estimated to be 173,000 gpd/ft (23,100 ft²/day).

Based on well completion reports provided by water well drillers, numerous irrigation wells have been drilled in the alluvium since 1985 between the towns of Winfield and Old Monroe, and also between Old Monroe and the confluence of the Mississippi and the Missouri rivers. Thicknesses of alluvial material in these wells averaged about 90 ft, and thicknesses of 150 ft in some parts of the valley are possible.

Storage estimates for the Mississippi River alluvium in Pike and Lincoln counties indicate that this aquifer in Pike County contains about 77.4 billion gallons, or 237,600 acre-ft,

while in Lincoln County it contains 124.4 billion gallons, or 381,600 acre-ft.

There are more data for the Mississippi River alluvial aquifer in northern St. Charles County. Thicknesses of 150 to 170 ft have been reported, with yields as high as 2,000 gpm not being unusual. Drawdowns of properly constructed and developed wells pumping large amounts of water have usually been less than 10 ft. This implies that specific capacities of 200 gpm/ft are possible, and that transmissivities could approach 300,000 gpd/ft (40,000 ft²/day). Although few irrigation wells have been reported in the alluvium of St. Charles County, there are numerous wells in the area that are used to flood large, shallow ponds at private waterfowl hunting clubs. There has also been widespread industrial use of the alluvial waters.

There is an area in the alluvium, just to the north of the city of St. Peters, in which the alluvial waters have elevated chloride levels. Here, the city of St. Peter uses six wells in the Mississippi River alluvium as a raw water source. Five of the wells are within an 11-acre tract; the sixth well is a short distance to the east. Production reportedly ranges from 400 gpm to about 1,500 gpm, and chloride content is about 130 mg/L. Since this area is on the eastern side of the freshwater-salinewater transition zone, the elevated chloride levels may be due to leakage of highly-mineralized groundwater from bedrock horizons into the alluvium.

The lithologic characteristics of the alluvial deposits are varied. The Mississippi alluvium is composed of silt, clay, fine- to coarse-grained sand, and fine to medium gravel. Since the alluvial materials were deposited by a meandering river throughout a several thousand year period, there is no areal uniformity; nor is there any continuity in the vertical sequence of deposits. However, generally there does seem to be coarser, more permeable material near the center of the valley or near the channel of the river, and finer material near the valley walls, especially near the base of the alluvium.

With the exception of counties in the Southeastern Lowlands, St. Charles County contains the greatest volume of groundwater in the Mississippi River alluvium—about 563 billion gallons or about 1.73 million acre-ft.

There is a small area of the city of St. Louis underlain by alluvial material associated with the Mississippi River. This area, locally known as Columbia Bottom, is about an 8.8-square-mile area located just south of the confluence of the Missouri and the Mississippi rivers. This area has alluvial thicknesses that average about 120 ft. The Division of Geology and Land Survey has maintained a groundwater-level observation well in Columbia Bottoms for almost 30 years. This well is 125 feet deep and shows fluctuations in water levels that closely mirror river-stage changes on the two rivers. Water levels below land surface average approximately 20 ft during normal years. In 1993, however, as river stages rose, water levels in the well rose in response. When flood waters were at floodplain elevation, groundwater levels were also essentially at land surface. Despite the fact that the casing for this observation well extends about 10.5 ft above ground level, the recorder was completely inundated after the levy failed during the 1993 flood.

The Mississippi River alluvium in St. Louis County and city is estimated to contain about 30.3 billion gallons, or about 93,000 acre-ft of water in storage during average periods. Although the overall quality of the alluvial water is generally good and is more consistent than that of Mississippi and Missouri river water, all of the St. Louis City and County public water supplies use intakes in the Missouri, Mississippi and Meramec rivers as raw water sources.

STE. GENEVIEVE COUNTY

A small area of about 8-square miles in eastern Ste. Genevieve County is underlain by Mississippi River alluvium. Very little data exists for this area except for a municipal well drilled for the city of St. Marys. St. Marys is

perched on the edge of the Mississippi River floodplain in an area where the Illinois-Missouri state line is only a few hundred feet northeast of the town. However, the Mississippi River is nearly four miles farther to the northeast. The Mississippi River changed its path here during a flood in 1881, leaving a 24-square-mile area of Illinois called Kaskaskia Island on the west side of the river. St. Marys' well was completed in an area of the alluvium, close to the edge of valley where the alluvial deposits are relatively thin. The well is only 53 feet deep, and only the lower 25 feet had sand coarse enough to be water-productive. The yield of the well reflected the lack of permeable sand and gravel, being only about 50 gpm. If St. Marys had constructed the well a few thousand feet farther to the east, in Illinois, it would likely have had a considerably better yield.

The volume of water stored in the Mississippi River alluvium in Ste. Genevieve County is relatively small, about 12.5 billion gallons, or about 38,400 acre-ft.

PERRY COUNTY

The area in northern Perry County underlain by alluvium is one for which very little data are available. The Division of Geology and Land Survey has logs of only two wells that penetrate the alluvial material in this 43-square-mile area. These wells indicate that there is at least 150 feet of alluvium, and that the alluvial material consists of fine- to coarse-grained sand, and fine to medium gravel. The hydrologic characteristics of the alluvium here are probably similar to those of the alluvium in the Bootheel further to the south. The potential for high-yield alluvial wells is good, but only a test-drilling program will establish a suitable site where sufficient permeable sands and gravels are present.

The 43-square-mile area of Mississippi River alluvium in Perry County is estimated to contain about 175 billion gallons of groundwater, or about 536,600 acre-ft.

GROUNDWATER QUALITY

Water produced from the Mississippi River alluvium, like that of the alluvium in the Southeastern Lowlands, generally meets public drinking water standards with the exception of iron and manganese. The elevated levels of these constituents are particularly high where the production wells are located a considerable distance from the river. Deeper alluvial water may contain higher levels of these metals than shallow alluvial water. Data indicates that high-yield wells

drilled close to the river will induce recharge from the river, and both iron and manganese will be significantly lower. Most municipal water supplies that use alluvial water have extensive treatment plants that are capable of removing the excess iron and manganese. It is not uncommon for the alluvial water to contain iron in excess of 20 mg/L, and have manganese concentrations of more than 3 mg/L, far in excess of recommended levels of 0.3 mg/L and 0.05 mg/L, respectively.

MISSOURI RIVER ALLUVIUM

INTRODUCTION

The Missouri River forms the western border of Missouri between Iowa and Kansas City, and bisects the state between Kansas City and St. Louis where it enters the Mississippi River, a total distance of about 533 miles. Like the Mississippi River, the Missouri River has carved a valley that contains up to about 150 ft of highly-permeable alluvial sediments. The alluvium underlies the Missouri River floodplain, which in Missouri ranges in width from zero, where the river hugs the bluff line in several places, to a maximum of about 12 miles. In general, the valley is widest upstream from Glasgow in Howard County. Between Glasgow and St. Louis, the valley is generally two to three miles wide.

The Missouri River, as it exists today, is much different than its ancestral counterpart that existed prior to Pleistocene time. Prior to the advance of the continental ice sheets into what is now Missouri, it is thought that the ancestral channel of the Missouri River in northwestern Missouri followed a route near what is now the Grand River. The Grand River confluence with the Missouri River today is at the southern edge of Chariton County. The part of the Missouri River valley between Kansas City and Chariton County was formerly occupied by the ancestral Kansas River. The modern Kansas River joins the Missouri at Kansas City. Continental ice sheets several thousand feet thick are responsible for the drainage changes. As the glaciers advanced into Missouri, the ances-

tral Missouri River was blocked with ice. Water from the drainage upstream of the blockage was diverted to the south and west, forming new drainage channels. After the melting of the ice sheets, the original drainage patterns were not reoccupied. The geomorphology of the valley upstream from the confluence of the Grand, and the placement and number of upland stream terraces, seem to confirm this theory.

Melt water from glaciers during the Pleistocene generated tremendous volumes of runoff, carrying immense quantities of sediment that had to be transported by the Missouri River. In response, the river carved a much deeper and wider channel than the river occupies today. Glacially-derived sediments ranging in size from clay particles to boulders were transported in the melt water. A considerable thickness of the sediments was deposited within the river valley to form the Missouri River alluvial aquifer.

The Missouri River alluvium is a very important and widely used water source in Missouri. Twenty-five counties in Missouri border the Missouri River, and nearly all of them make use of water available from the alluvium. Wells drilled into the alluvium supply much of the water for numerous rural water districts, towns and cities including Kansas City, Independence, Columbia and St. Charles. In addition, hundreds of high-yield irrigation wells are used throughout the reach of the Missouri River to enhance agricultural production.

As with the Mississippi River, there is direct interchange between the river and the alluvium. Groundwater levels are directly related to the stage of the river, although there is a delayed response of several days between higher river stages and higher groundwater levels. Figure 54 is a water-level hydrograph of a groundwater-level observation well completed in the alluvium of the Missouri River at Jefferson City and maintained by the Division of Geology and Land Survey. River stage data from the U.S. Geological Survey gaging station at Boonville, about 20 miles upstream of Jefferson City, are also shown. Seasonal river stages are illustrated by the gradual decline of water levels during the fall and winter months, and the gradual rise of groundwater levels starting in early spring through summer

months. It can also be seen that, unlike bedrock wells located in the Ozark Province, the alluvial aquifer does not respond appreciably to local rainfall events.

Depending on location and local geology, the Missouri River alluvial aquifer can either be confined or unconfined. In places, the upper 20 to 30 ft of the alluvium consists of low-permeability materials. The potentiometric surface of the aquifer is typically within a few feet of the water-surface elevation of the river. Locally, the base of the clay and silt may be below the potentiometric surface, causing artesian conditions to exist. In other places, particularly those where there is a relatively thin clay and silt cap and the uppermost alluvial materials are very sandy, the aquifer is unconfined and water table conditions exist.

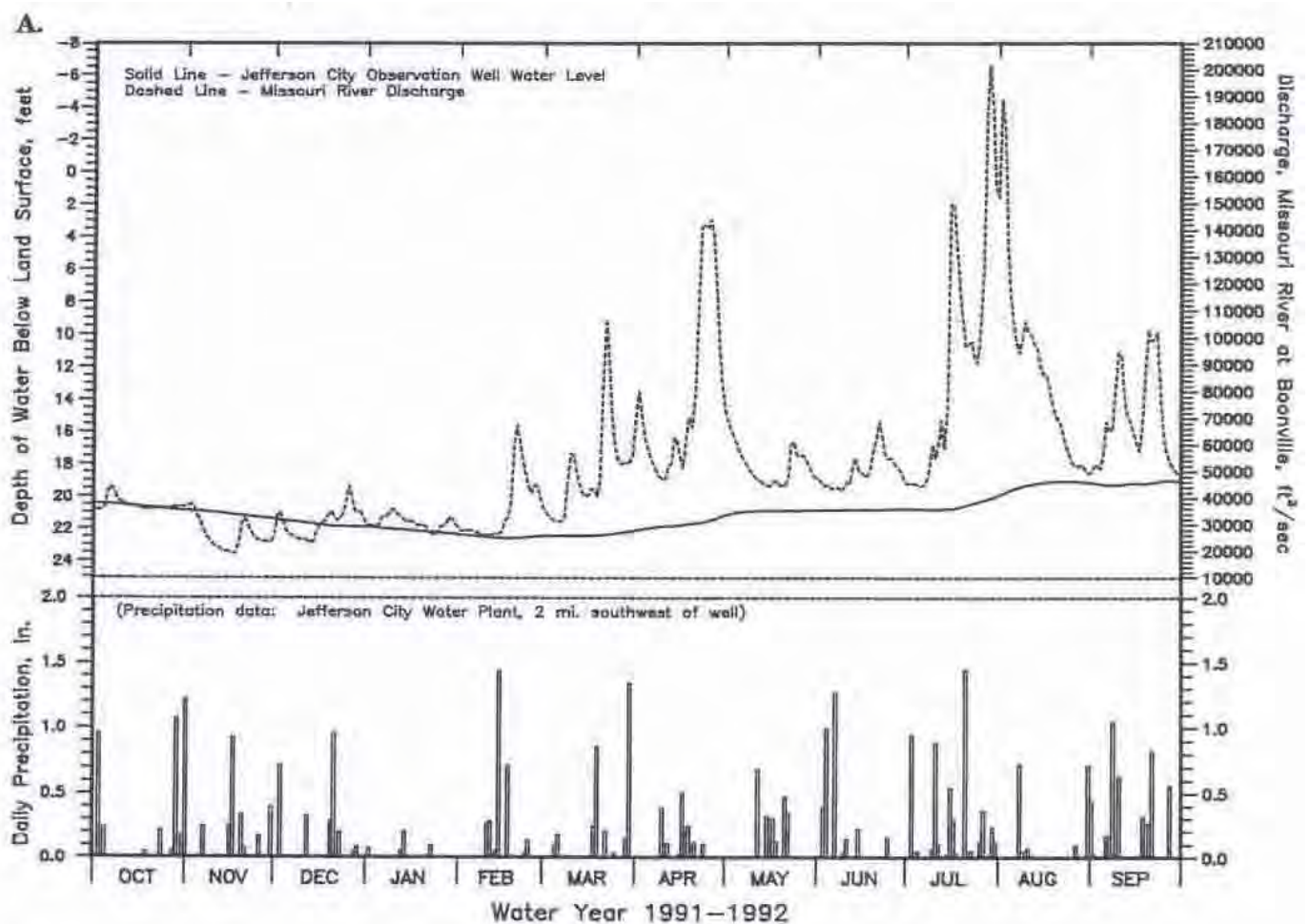


Figure 54 a & b. The relationship between groundwater level, Missouri River discharge and local precipitation at Jefferson City. Figure 54a shows relatively low river flow during the first half of water-year 1991-1992.

Although confined conditions are locally possible, under normal conditions alluvial wells cannot be under flowing artesian conditions. An exception to this is where levies have been constructed along the river. During flood periods, the potentiometric surface of the alluvial aquifer could be high enough to allow alluvial wells to flow near the river. Water levels in the alluvium normally range from less than five feet below land surface to approximately 20 ft below land surface. In most instances, the elevation of the drill site or well above river level dictates what the static water level will be.

When the Missouri River is under normal flow conditions, groundwater gradients in the Missouri River alluvium are towards the river, with a vector of about 45 degrees in a down-

stream direction. These gradients are very gentle, generally less than one to two feet per mile, and the velocity of groundwater movement through the alluvium is quite slow. Assuming an aquifer transmissivity of 200,000 gpd/ft (26,700 ft²/day), a saturated thickness of 75 ft, a hydraulic gradient of 2 ft/mi, and an effective porosity of 30 percent, groundwater velocity is about 0.5 ft/day. This is a very low velocity when compared to those measured in the thick carbonate aquifers in the Ozarks where, under certain conditions, velocities can exceed a mile per day. The reason for such low hydraulic gradients and slow velocities is that the flow in the alluvial sediments is intergranular flow, or flow between the individual sand or gravel particles, whereas the flow in carbonate systems is usually along solutionally

B.

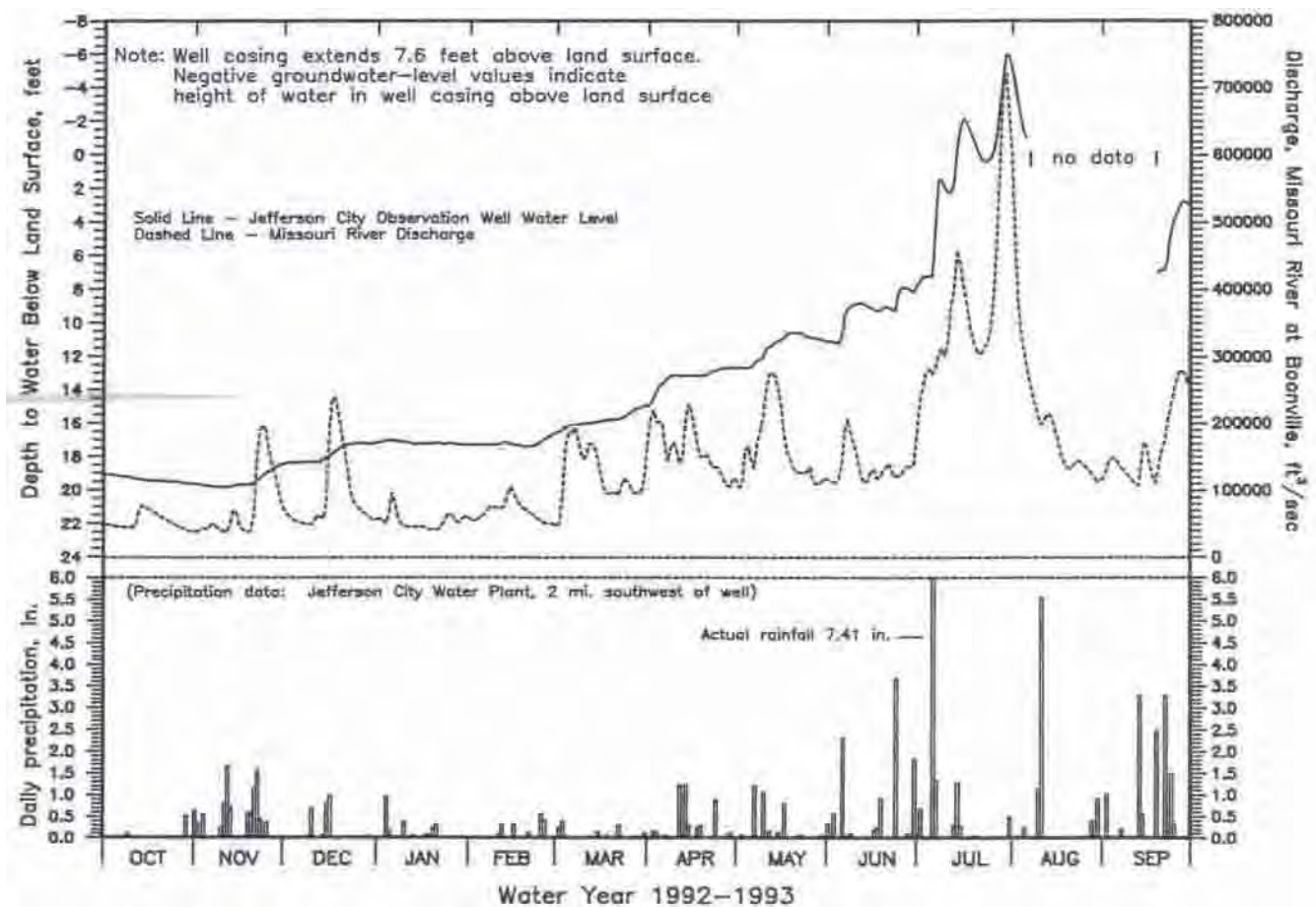


Figure 54b. The effect of prolonged high river stages on water level in the alluvial aquifer was very apparent during the Great Flood of 1993. (River discharge measured at Boonville.)

enlarged cracks and crevices, and in cave-like conduits.

The Missouri River alluvium receives recharge from four sources: infiltration from the Missouri River, from bedrock adjacent to and underlying the alluvium, from precipitation falling upon the floodplain, and from downward leakage of water from streams flowing across the alluvium. Water from the Missouri River recharges the alluvium generally under two conditions. When the river is at a high stage, that is above the elevation of the potentiometric surface, there is recharge of the alluvium from the river. Recharge also occurs where high-yield wells are constructed close enough to the river so that when they are pumped they induce direct recharge from the river to the well. The potentiometric surface of bedrock aquifer units adjacent to the Missouri River is normally above the potentiometric surface of the alluvial aquifer. Thus, there is groundwater movement from the bedrock into the alluvium. The volume of water supplied by precipitation, and the volume of recharge that occurs from other streams as they cross the Missouri River alluvium, depends greatly on the hydrologic characteristics of the shallow alluvial materials. In areas where the surficial materials are sandy and permeable, the amount of recharge water is significant. Where there is a clay or silt cap overlying the more permeable deposits, the recharge is less.

The alluvial materials of the Missouri River valley are composed of clay, silt, fine to coarse sand, and fine to medium gravel. The size of the alluvial materials typically increases with depth; finer-grained materials directly underlie the land surface and coarser sands and gravels are found at greater depth. This clay or silt cap overlying the more permeable sands and gravels, where present, will retard infiltration of surface water. Since these sediments were deposited by a meandering stream over long periods of time, there is no definite sequence of deposition at any particular site. The alluvium ranges in thickness from a feathered edge at the edge of the valley to as much as 150 ft. The alluvium is generally the thickest

in the center part of the valley near the river, but there are instances where the thickest materials are near a valley wall.

The volume of water stored in the Missouri River alluvial aquifer varies somewhat, but is estimated to be about 3.3 trillion gallons, or about 10.2 million acre-ft. The county containing the greatest volume of storage is Holt County, where the alluvial aquifer underlies an area of about 182 square miles, or about 40 percent of the county. Here, the saturated thickness of the aquifer averages about 80 ft, and it is estimated to store about 455 billion gallons, or about 1.4 million acre-ft. Gasconade County contains the least volume of water in the Missouri River alluvium. Here, the river tends to follow the valley wall on the Gasconade County side of the river, and alluvium underlies only about seven square miles. The volume of water in the alluvium in Gasconade County is estimated to be about 18 billion gallons, or about 55,300 acre-ft.

For ease of discussion, the Missouri River, from its entrance point in extreme northwestern Missouri to its confluence with the Mississippi River at the eastern edge of the state, has been divided into four reaches; the Iowa border to Kansas City, Kansas City to Miami in Saline County, Miami to Jefferson City, and Jefferson City to St. Charles (figure 55). These divisions are not arbitrary. The U.S. Geological Survey (Emmett and Jeffery, 1968, 1969a, 1969b, 1970) prepared a series of hydrologic atlases to describe the groundwater characteristics of the Missouri River alluvium and used the same boundaries. Since this is the most detailed information available for much of this alluvial aquifer, the present report will follow the same format.

IOWA STATE LINE TO KANSAS CITY

A 1968 study conducted by the U.S. Geological Survey (Emmett and Jeffery, 1969b) is the most recent investigation of the Missouri River alluvium in this reach. At that time, nine communities, 12 industrial well fields, and approximately 50 irrigation wells were using alluvial water in this 446-square-mile area. Considering the poor bedrock groundwater

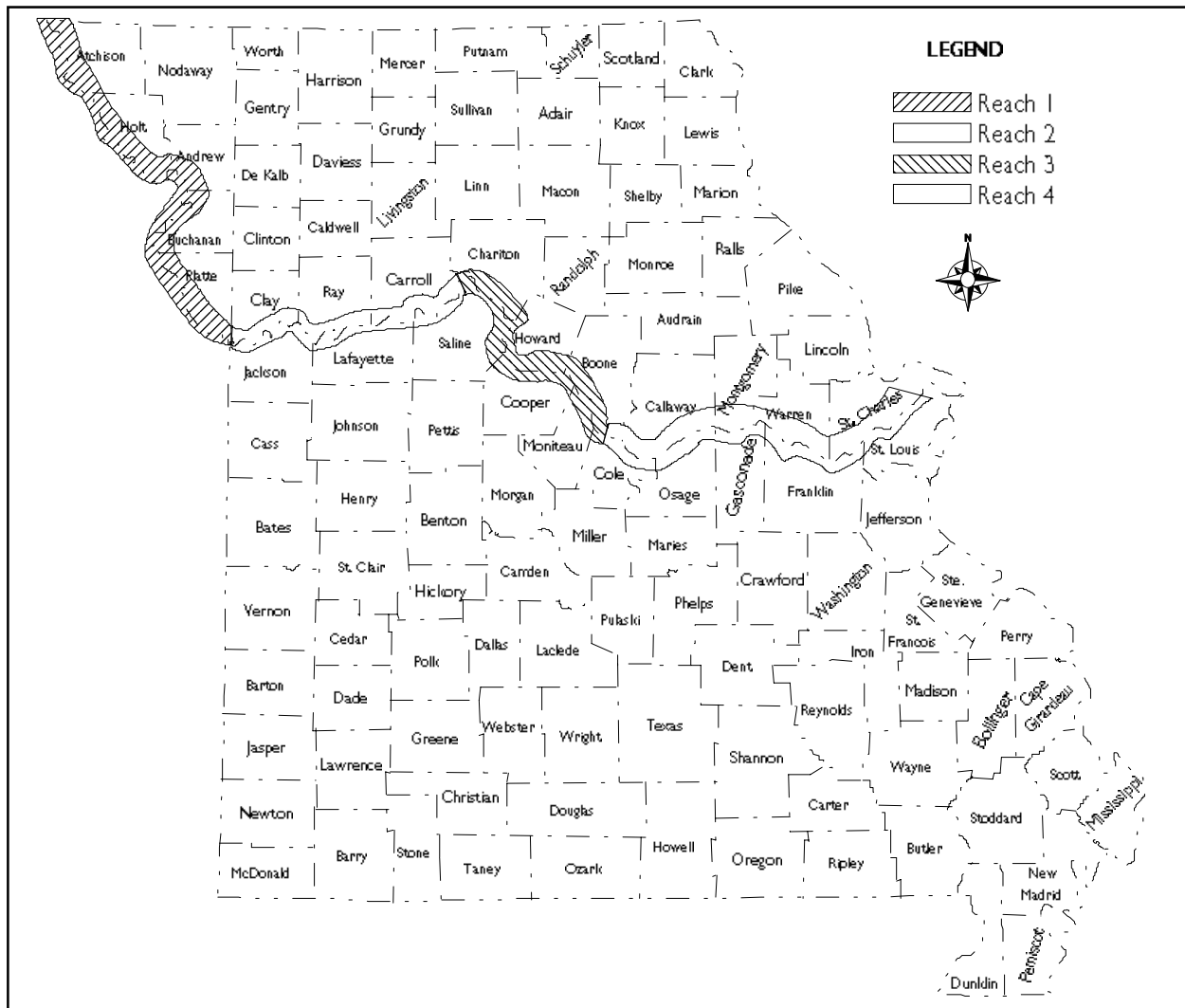


Figure 55. Index map showing locations of the four reaches of the Missouri River alluvium discussed in this report.

resources of this area, and the periods of drought experienced in this part of Missouri in the late 1970s and early 1980s, it is quite probable that these numbers have increased significantly, particularly the number of irrigation wells.

The average thickness of alluvium in this reach has been reported to be approximately 90 feet (Emmett and Jeffery, 1969b) and the average saturated thickness is about 80 feet. It generally consists of several feet of clay and silt near the surface, underlain by sand and gravel (figure 56). The alluvium in this area is underlain by Pennsylvanian-age shales, limestones and sandstone. The Pennsylvanian-age units are not considered important aqui-

fers. They yield very little water, and the water they contain is generally too highly mineralized for most uses.

There are glacial deposits in upland areas adjacent to the river valley that may be hydraulically connected to the alluvium, and may recharge to the alluvium. Test drilling adjacent to this reach of the river has also found thicknesses of unconsolidated deposits, which indicate the presence of preglacial channels (Heim and Howe, 1962). Undoubtedly, these channels are connected to the alluvium of the Missouri River, but the volume of recharge they supply to the alluvium is not currently known.

The alluvium is recharged by infiltration from the river in upstream reaches, infiltration

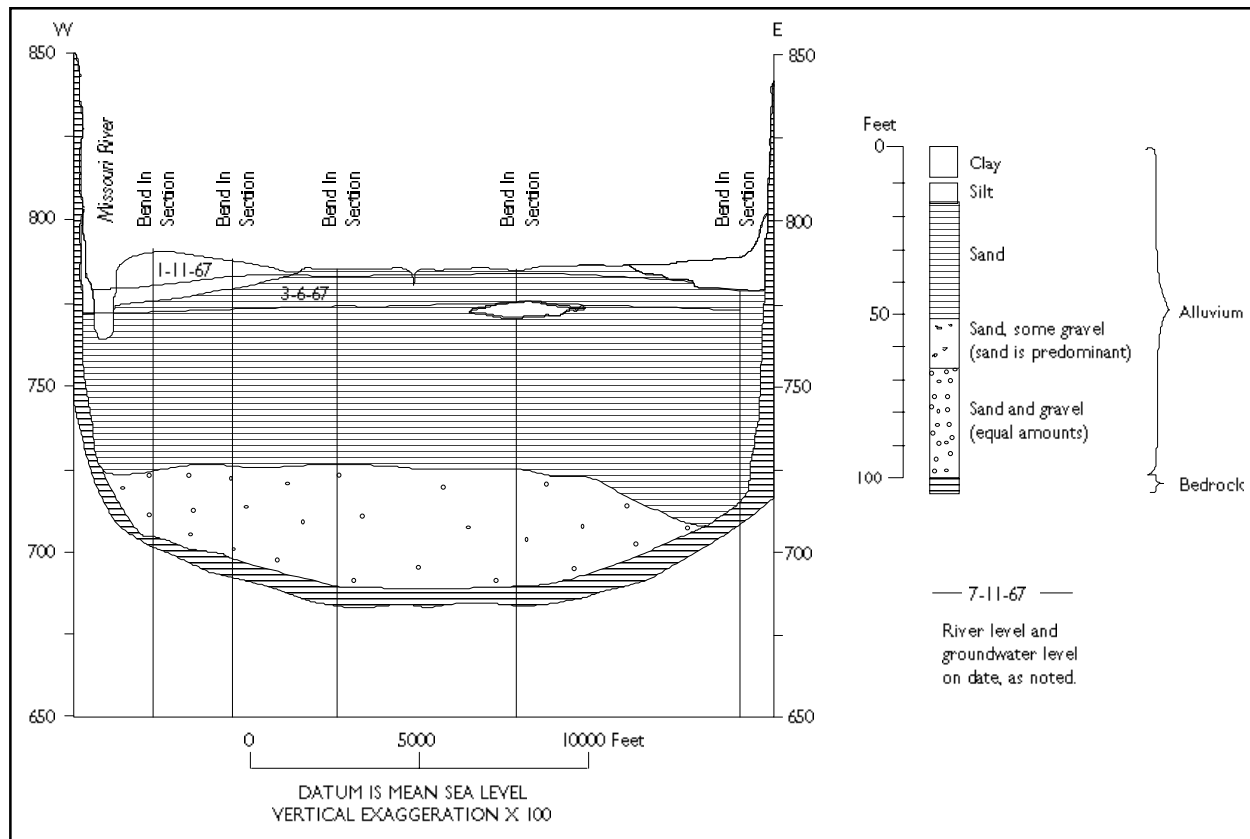


Figure 56. Cross-section of the Missouri River alluvium near St. Joseph, Missouri (from Emmett and Jeffery, 1969b).

from streams flowing across the alluvium and towards the river, by infiltration or leakage of water from bedrock sources, and precipitation. Recharge from precipitation is probably about 6 inches per year, or about 1.86 million gallons per year per square mile, which is a very small amount when compared to recharge the alluvium receives from the river. Discharge from the alluvium to the river is the main source of depletion of the aquifer.

During prolonged drought periods when the river stage is low, discharge from the aquifer to the river is more pronounced. This is due to a steepening of the hydraulic gradient toward the river. During prolonged periods of high river stage, the gradient is reversed, and recharge from the river into the alluvium takes place. However, in either case, the largest amount of groundwater-level fluctuation always takes place in zones nearest to the river.

Early hydrologic work in the Kansas City area indicated that well yields from Missouri River alluvium averaged approximately 1,000 gpm with specific capacity averaging about 60 gpm/ft of drawdown (Fishel and others, 1953). Many wells in this reach of the river yield more than 2,000 gpm, and have specific capacities of 80 to 90 gpm/ft of drawdown. Assuming an effective porosity of 15 percent throughout this reach, and an average saturated thickness of 80 feet, it is calculated that the Missouri River alluvial aquifer normally contains about 1.1 trillion gallons, or about 3.4 million acre-ft during average periods. In 1968, the average computed use of the resource was only 18 mgd (Emmett and Jeffery, 1970), indicating that only a very small part of the total aquifer potential is being used.

Yields of individual wells can be increased if the well is located to induce re-

charge into the aquifer from the river. The reasons for this practice are to ensure better quality water, lower pumping costs and decrease drawdown in the well. This has the added advantage of creating lower entrance velocities into the well through the well screen, an important factor in reducing the rate of mineral incrustation on the screen. Incrustation, which is the deposition of minerals such as iron or calcium carbonate on the well screen, is caused by dissolved minerals precipitating on the well screen. Over a period of time, well-screen incrustation will cover the openings of the screen and greatly reduce well yield. The problem can be diminished by proper well design and construction, and proper pumping operations. The well should be designed and constructed to allow water to enter the well with minimal resistance. A well screen having a large percentage of open area will reduce the entrance velocity of the water and minimize drawdown. Pumping the well at a higher rate than that for which it was designed can lead to more incrustation. The permanent pump should be selected only after the well has been fully developed and pump-tested. This way, the most efficient pump can be selected to supply a volume of water the well can safely produce.

Despite these efforts, the yields of most alluvial wells will eventually decrease because of screen incrustation, and the wells will need to be serviced to recover the lost production. Cleaning the incrustation from well screens typically involves the introduction of muriatic (hydrochloric) acid into the well adjacent to the screen. The acid should have some sort of buffering chemical added to minimize the corrosive effect on the metal in the screen. The acid will dissolve the carbonate-rich scale or incrustation, and generally restore the production of the well to near its original value.

Groundwater quality in the alluvium of the Missouri River in this reach is rather typical of alluvial aquifers. In instances where the water is pumped from wells at some distance from the river, it is a moderately mineralized calcium-bicarbonate type, and is usually high in iron and manganese. Iron concentrations average as high as 6.0 mg/L and manganese averages

about 3.0 mg/L. If the well is located near the river where increased infiltration from the river can be induced, then the total iron and manganese content will be much lower. In most instances, water treatment to remove iron and manganese is necessary if the water is to be used for municipal or domestic purposes. If wells are located in areas where appreciable amounts of leakage from bed-rock sources is occurring, then the alluvial waters may contain elevated concentrations of both sodium and chloride.

KANSAS CITY TO MIAMI

The reach of the Missouri River from Kansas City to Miami in Saline County is approximately 109 miles long, and the areal extent of the alluvial aquifer is approximately 440 square miles (Emmett and Jeffery, 1970). Pennsylvanian-age limestones, shales and sandstones underlie the alluvium throughout most of this reach. These bed-rock formations generally have very low hydraulic conductivities, and the water within them is generally highly mineralized in much of the area along this reach of the river.

The upper part of the Missouri River alluvium in this reach is composed of fine sand, silt and clay, while coarser sands and gravels comprise the deeper part of the alluvial fill. In this reach, the maximum thickness is approximately 140 ft, with an average thickness of about 85 to 90 ft. Water levels in the alluvium range between 5 and 20 ft below land surface, and the average saturated thickness is about 70 ft. Figure 57 is a cross section across the Missouri River valley near Miami, in Saline County, showing the character and thickness of the alluvial material.

Heim and Howe (1962) show numerous buried valleys in this reach of the river. Most noteworthy is what appears to be a cutoff meander of the ancestral Missouri-Kansas River near Lake City, in northeastern Jackson County, and a larger channel in Saline County, which starts near Malta Bend. The latter trends in a southeasterly direction and reconnects with the present Missouri

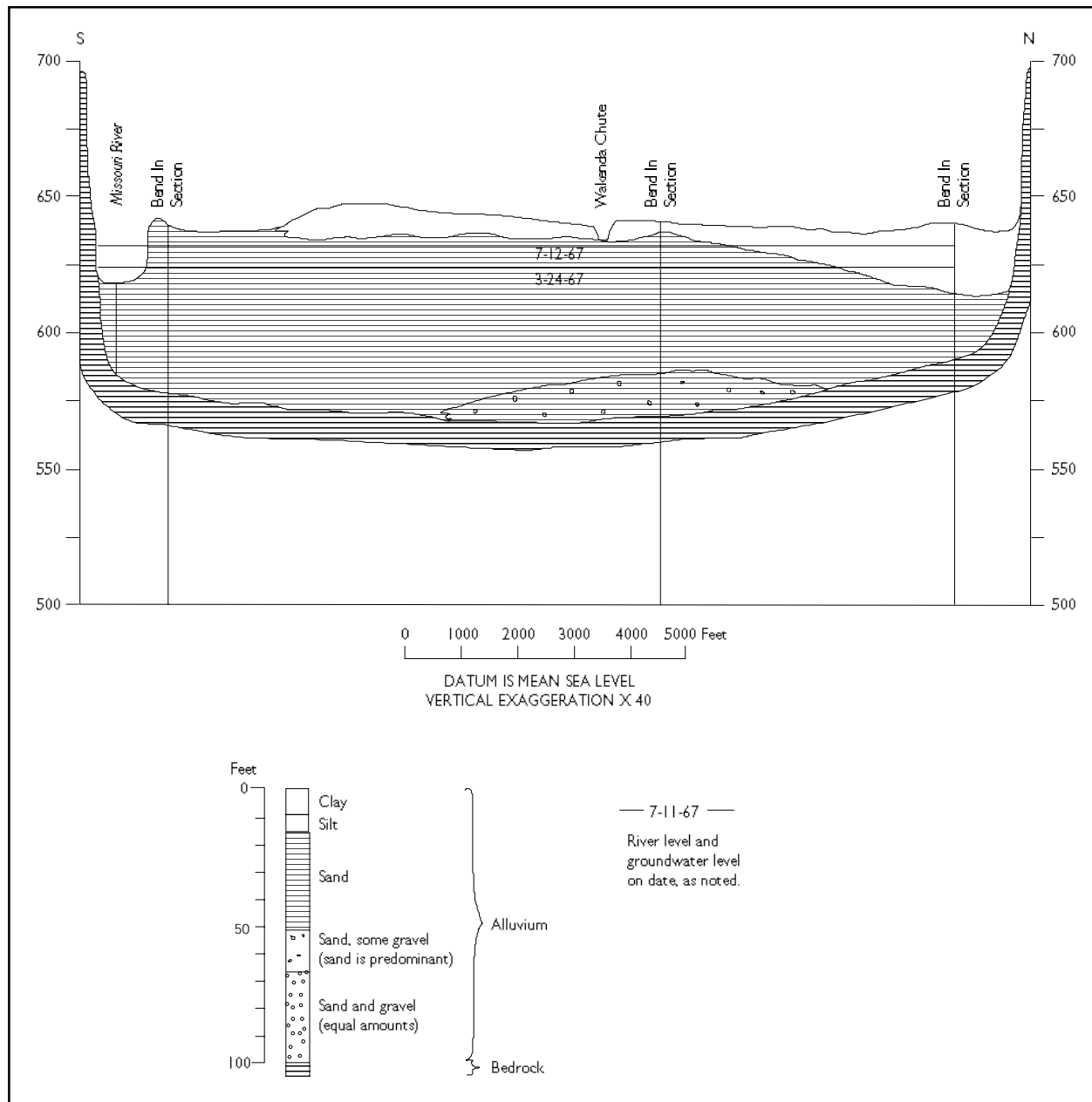


Figure 57. Cross-section of the Missouri River alluvium near Miami in Saline County (from Emmett and Jeffery, 1970).

River valley east of Arrow Rock in northern Cooper County, a distance of approximately 38 miles. This latter channel is probably the result of glacial damming or relocation of the river during glaciation. Figure 58 shows the approximate southern extent of glacial ice at its furthest encroachment into Missouri.

The development of terraces along the Missouri River, or any major river, is a subject that deserves mention. A terrace surface marks a former floodplain elevation. Downcutting or undercutting by the river during periods of degradation leaves the terrace at some elevation above the present floodplain. In some

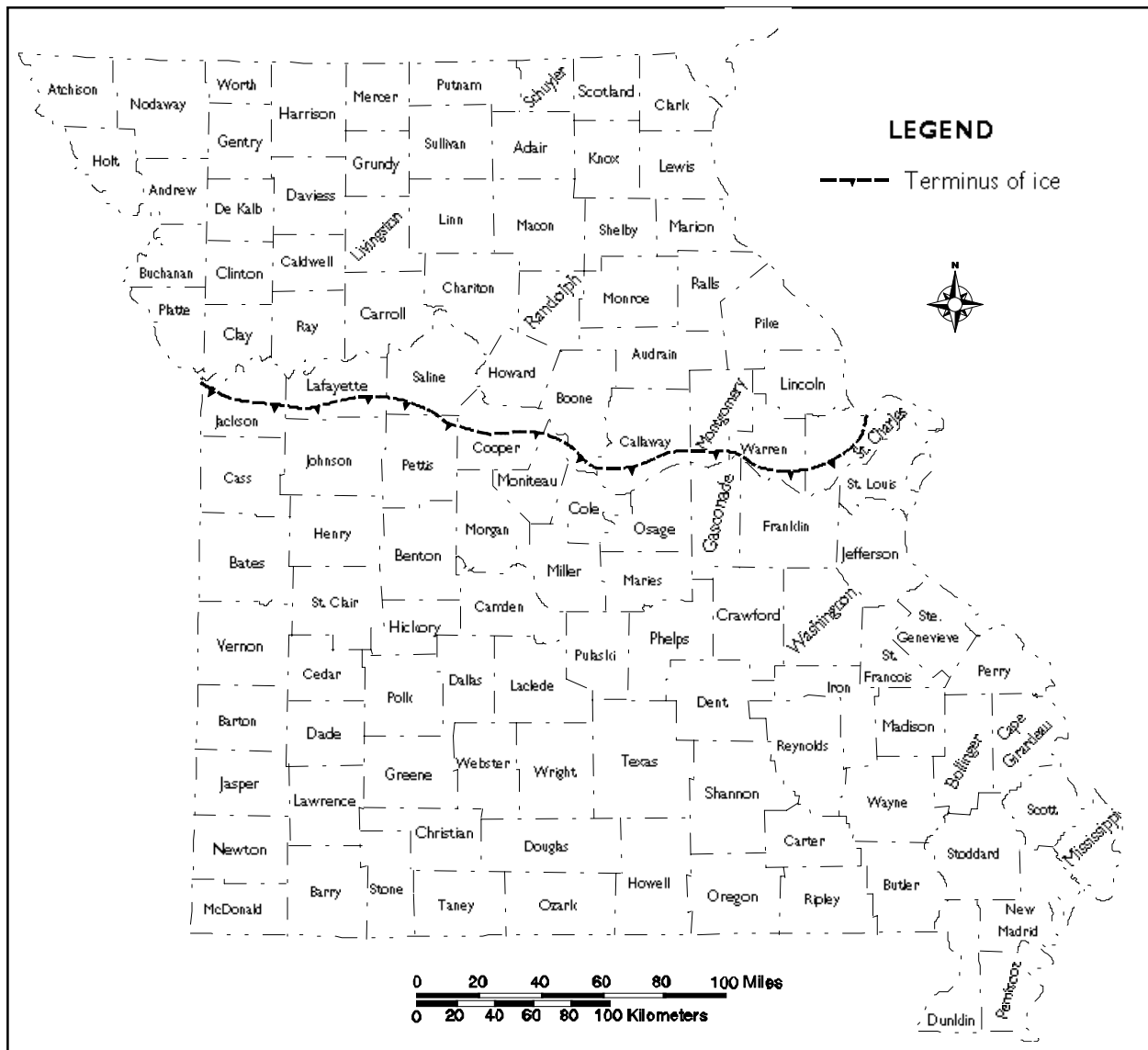


Figure 58. Approximate extent of glacial ice in Missouri.

places along the river there is a series of terrace levels that mark floodplain-remnants remaining after several different phases of downcutting. These downcutting or degradation events probably mark different phases where the regional base level of erosion changed. Underlying some of these terraces

are fairly thick sand and gravel deposits that may be saturated with water. There is undoubtedly a hydraulic connection between the groundwater underlying the terraces and the alluvial materials. One such terrace along the Missouri River, which is used as a source of water, deserves mentioning. It is the

Teteseau terrace in northwestern Saline County (Emmett and Jeffery, 1970). This terrace surface is 50 to 60 ft above the present Missouri River floodplain level, and wells producing from it are a source of water for the city of Marshall. The presence of the terrace and its height above the present drainage is probably the result of the blockage of the original channel by glacial ice, and quite probably the terrace developed at the same time that the previously mentioned glacial-age channel traversing Saline County developed. There is a definite need for additional work on river history and the terrace deposits along this reach of the Missouri River.

Presently, there are eleven cities that pump a total of about 15 mgd from the alluvium in this reach (DNR, 1991). Industrial use appears to be limited to the Kansas City area. Emmett and Jeffery (1970) estimate industrial use to be about 13 mgd; more recent data are not available. Numerous irrigation wells are also present, and although pumpage is seasonal and mostly supplemental in nature, pumpage has been approximated to be 1.25 mgd. The total use of alluvial water in this reach of the Missouri River is estimated to be 30 mgd, which is a small percentage of the 1.04 trillion gallons of alluvial aquifer storage estimated for this reach.

Yields of 1,000 to 1,500 gpm are not unusual from production wells drilled through the more permeable zones in the alluvium. These wells have specific capacities of from 50 to 150 gpm per foot of drawdown (Emmett and Jeffery, 1970). Transmissivities range from 150,000 to 250,000 gpd/ft (20,050 to 33,400 ft²/day).

Like the previously discussed segment of the river, this reach has variable water quality, both spatially and temporally. Total dissolved solids range between 250 mg/L to as high as 1,200 mg/L. In areas of poor circulation due to low permeability, the dissolved solids content of the water is usually higher due to longer residence time of the water in the aquifer. However, the highest levels of mineralization are commonly due to leakage of mineralized water from the bedrock aquifers

into the alluvium. As with most groundwater in Missouri, whether it be from bedrock sources or from alluvial sources, calcium and bicarbonate are the most prevalent dissolved constituents. Where there are additions of groundwater from bedrock sources, magnesium and sulfate may be significant. In these instances, sodium and chloride will also be present in varying amounts. As is the case with most alluvial waters, iron and manganese contents are typically high. Water treatment to reduce iron and manganese is necessary for most wells that supply water for municipal or private domestic needs.

MIAMI TO JEFFERSON CITY

The Missouri River from Miami to Jefferson City is 116 miles long, and alluvium in this reach underlies about 291 square miles. In the upstream part of this reach, from Miami to about the southeastern corner of Howard County, the alluvium overlies bedrock formations that contain highly mineralized water. Downstream from here, the bedrock beneath the alluvium contains fresh water with less than 1,000 mg/L total dissolved solids. The bedrock units in the lower part of this reach also tend to have greater permeabilities than those upstream, and probably discharge more water into the alluvium.

Data indicate an average alluvial thickness of approximately 80 ft, with a maximum thickness of about 95 ft. The average saturated thickness is estimated to be 60 ft (Emmett and Jeffery, 1969a). The average thickness of the alluvium in this reach is actually less than it is upstream. This apparent gradual thinning of the alluvial material in a downstream direction is unusual. With most rivers, the thickness of the alluvial materials usually increases in a downstream direction, or remains fairly constant. There is also a significant narrowing of the valley near Glasgow, in Howard County where the valley width narrows from approximately 6.1 miles to just under 2.0 miles in a distance of 10 miles. There also appears to be a slight gradient change downstream from Glasgow. These factors, coupled with the presence of the high terrace upstream, the

abandoned glacial channel in Saline County, and the confluence of the ancestral Missouri (Grand) River just upstream, seem to indicate another major change, which took place in the Missouri River drainage during the latter part of the Ice Age. Based on drillhole information, it appears that an ancestral channel exists that roughly parallels the Missouri River a few miles to the north. This channel starts at the Missouri River between Glasgow and Boonville, and trends east across Boone County north of Columbia, northern Callaway County, and central Montgomery County. Evidence of its existence seems to end near Warrenton in central Warren County. The channel is filled with glacial deposits consisting of sand, gravel, silt, clay and angular fragments of igneous material. A great deal more work will be required to understand the sequence of events that created the drainage changes in this reach of the river, and to accurately delineate the exact location and terminus of this channel.

The lithologic character of the alluvial material in the modern channel of the Missouri River from Miami to Jefferson City is not appreciably different from that upstream, even with all of the apparent changes in drainage due to glaciation. Figure 59 is a cross section of the Missouri River at Boonville, in Cooper County, showing thickness and character of the alluvial deposits.

As with the upstream reaches of the river, only a small percentage of the available groundwater in storage in the alluvium is currently being used. Assuming an average saturated thickness of 60 ft, and an effective porosity of 15 percent, then approximately 546 billion gallons of groundwater is normally in storage. If only 15 percent of the annual rainfall of approximately 38 inches is recharging the alluvial aquifer, this would add a volume of about 88,000 acre-ft or about 79 mgd in this reach. This is the equivalent of 55 wells, each pumping 1,000 gpm, 24 hours a day for 365 days. Emmett and Jeffery (1969) estimated that combined irrigation, municipal, domestic and industrial use (by five cities at the time of the report), was less than 0.45 mgd, or less

than 1 percent of the recharge supplied by precipitation alone.

At the time that this estimate was made, the city of Columbia, in Boone County, used groundwater from bedrock wells. Presently, Columbia uses alluvial groundwater from 10 wells located in the McBain Bottoms and also has five auxiliary bedrock wells that bottom in the Potosi Dolomite. The current raw-water supply capacity of the alluvial well field is approximately 16 mgd; 1994 production from the well field averaged about 10 mgd. Aquifer pumping tests show that the transmissivity of the alluvium here is about 440,000 gpd/ft (58,500 ft²/day), and each well is capable of pumping from 725 to 1,400 gpm. Even with this large usage, the total daily withdrawal from the alluvium in this reach is less than 16.5 mgd, far less than its potential production.

From Rocheport, in western Boone County, to Jefferson City, in northern Cole County, the bedrock units underlying the alluvium contain fresh water, and probably contribute appreciable recharge. Also, groundwater gradients in the shallower bedrock zones are towards the river.

As described in discussion of upstream reaches, incrustation of well screens by excessive calcium carbonate, elevated iron and manganese concentrations, and worry about organic contaminants due to the extreme permeability of the aquifer are the primary water quality concerns.

Total dissolved solids concentration of alluvial water in this reach of the river typically ranges between 250 mg/L and 800 mg/L, with calcium, magnesium, and bicarbonate contributing the largest percentages. In the reach underlain by Pennsylvanian and Mississippian strata, sulfate, sodium, and chloride are present in higher concentrations than in the stretch underlain by Ordovician rock containing fresh water.

JEFFERSON CITY TO ST. CHARLES

The hydrologic characteristics of the Missouri River alluvium in this 147-mile reach are very similar to those in the reach

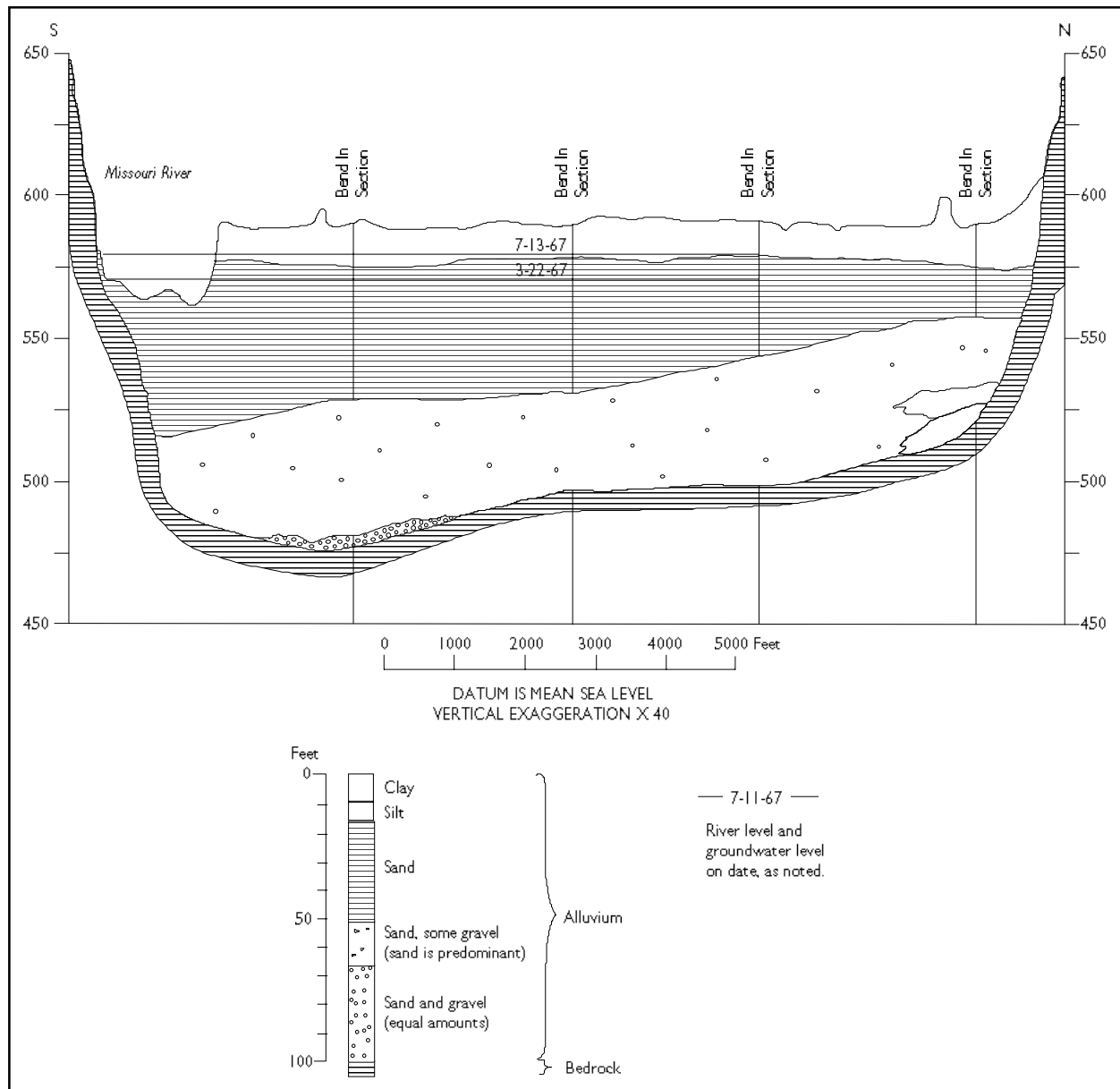


Figure 59. Cross-section of the Missouri River alluvium at Boonville, Missouri (from Emmett and Jeffery, 1969a).

between Miami and Jefferson City. From Jefferson City to northeastern Franklin County, the valley is developed in Ordovician-age bedrock. From northeastern Franklin County to its confluence with the Mississippi River, the valley is developed in Mississippian- and Pennsylvanian-age formations. Currently, the city of St. Charles is the only municipality along this reach of the river that has a well field that uses groundwater from the Missouri

River alluvium, but there are numerous water districts, industrial, and irrigation wells in the floodplain adjacent to St. Charles and St. Louis counties.

As with upstream reaches, the deeper part of the alluvium in this reach is composed of coarse sand and gravel, and the upper part grades to finer material near the land surface. The maximum thickness reportedly encountered by drill holes is approximately 120 ft,

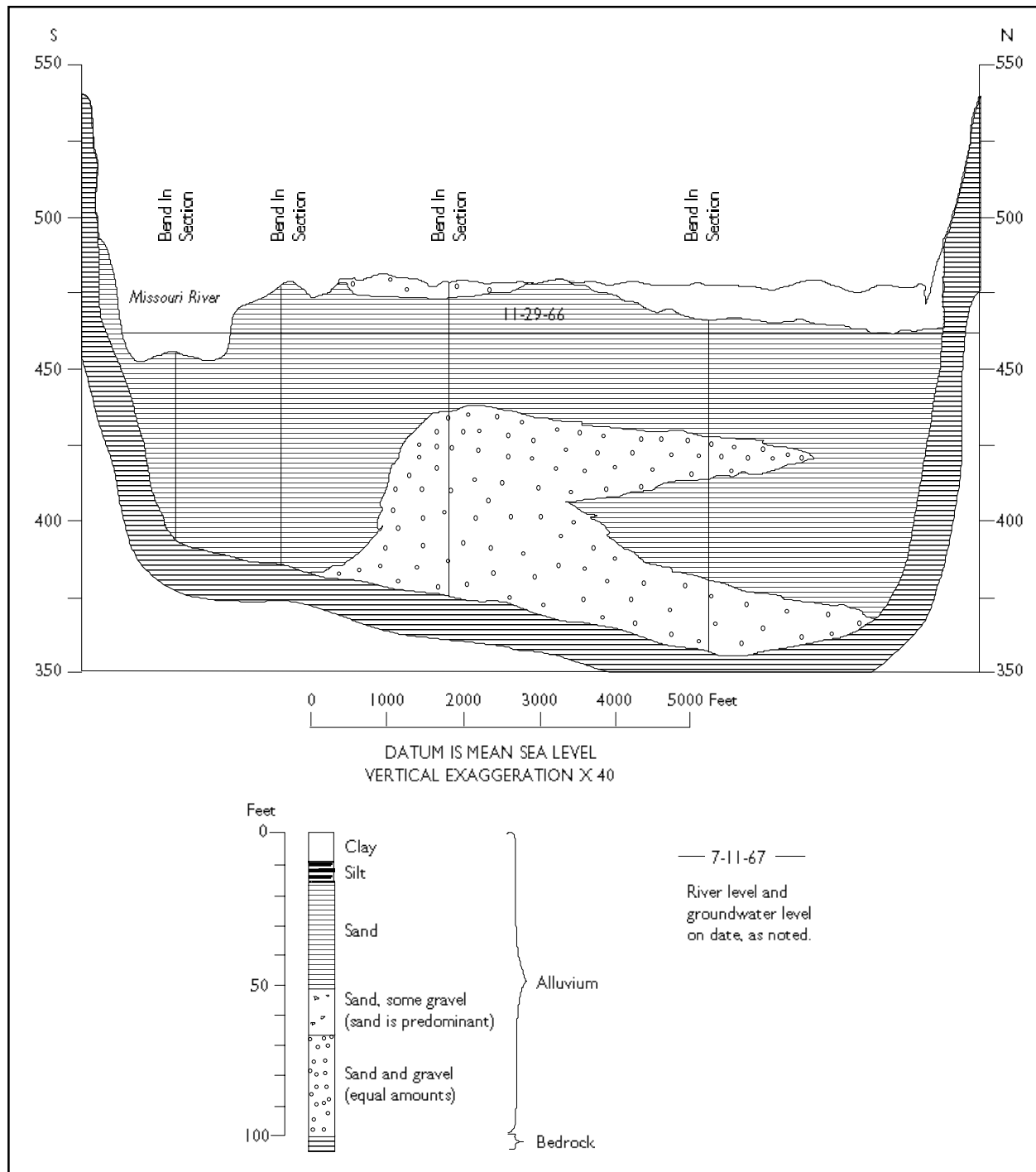


Figure 60. Cross-section of the Missouri River alluvium at Washington, Missouri (from Emmett and Jeffery, 1968).

and the average is 100 ft (Emmett and Jeffery, 1968). Figure 60 is a cross section of the valley at Washington in Franklin County, showing the character and thickness of the alluvial deposits.

As in the upstream reaches, recharge to the alluvium occurs during high river stages, from precipitation, and from bedrock groundwater entering the alluvium. However, leakage from bedrock sources is probably more

important in this reach than in the upstream areas. These formations, although not considered to be the principal or most permeable bedrock aquifers in the Salem Plateau, still yield significant volumes of water to the alluvium when the entire reach is considered.

The alluvial aquifer in this reach of the Missouri River underlies an area of about 224 square miles. Based on an average saturated thickness of 80 ft and an effective porosity of 15 percent, the alluvium contains about 560 billion gallons, or about 1.7 million acre-ft of water. Yields of properly sited and constructed alluvial wells in this area are favorable. Data from an U.S. Geological Survey test drilling program along this reach of the river indicates that in most places the alluvium is capable of yielding 1,000 to 3,000 gpm. Yields of from 2,500 gpm to 3,000 gpm, with transmissivities of 200,000 gpd/ft to 250,000 gpd/ft (26,700 ft²/day to 33,400 ft²/day), are not unusual.

The Missouri River alluvium in this reach may, depending on location and river stage, be under either confined or unconfined conditions. The Missouri River alluvium is unconfined where the surficial materials are sandy, or where the clay and silt cap is very thin. Where the clay and silt cap is relatively thick, the aquifer may be under confined conditions. In well fields along the river, the cone of influence from pumping of a high-yield well will generally be shallow, and of a relatively small areal extent. For example, a well producing 2,000 gpm from an aquifer with a transmissivity of 250,000 gpd/ft and a specific yield of 0.15 will create only about 5.7 ft of drawdown in the aquifer a distance of 100 ft from the pumped well after 10 days of continuous pumping. Drawdown in the aquifer adjacent to the well will be only about 15 ft, and 10 ft from the well it will be about 10 ft. In comparison, a high-yield bedrock well in the Salem Plateau pumping 1,000 gpm would likely create more than 100 ft of drawdown at a distance of 100 ft from the well after a few days of pumping.

Although alluvial wells along the Missouri River may be under confined conditions initially, extended pumping will lower the water level to below the base of the confining layer, and the aquifer will then be under water table conditions. Consequently, the storage coefficient of the alluvial aquifer will also change from a relatively small value, typically between 1×10^{-3} to 1×10^{-5} , to a relatively large value, about 0.15.

Because of the high storage coefficient, it is possible to place several high-yield wells in a relatively small area and still not create substantial drawdown. This is demonstrated at the well fields, that serve the two major public water supply users of alluvial groundwater along this reach of the river.

The well field that once served the Weldon Springs Ordinance Works in southeastern St. Charles County is now used to provide water to numerous rural residents, subdivisions, and other public water supplies in the area. Nine alluvial wells, four of which are very close to the river, have a combined maximum production of about 23,100 gpm, or about 33 mgd. The volume of water produced by St. Charles County Water Department in 1994 was reportedly about 3.62 billion gallons, an average of about 9.93 mgd.

The city of St. Charles and part of rural St. Charles County is supplied from a well field developed in the Missouri River alluvium at the north edge of St. Charles where the floodplains of the Mississippi and Missouri rivers converge. This well field consists of five wells drilled along a north-south line; the wells at the ends of each line are separated by about 2,000 ft, and adjacent wells are from 420 ft to 750 ft apart. All of the wells reportedly yield at least 1,000 gpm, which equates to a maximum potential yield of about 7.2 mgd. In 1994, the city of St. Charles reportedly used 778 million gallons of water, and had an average daily usage of 2.13 mgd.

GROUNDWATER QUALITY

The quality of the alluvial groundwater in this reach of the river is similar to that of the alluvial groundwater in the upstream reaches. It is generally a moderately mineralized calcium-magnesium-bicarbonate type. Iron and manganese generally exceed public drinking water standards by substantial amounts, particularly in those areas where circulation is restricted such as close to the valley walls or where the permeability of the aquifer material is low. In areas where there can be direct interchange or recharge from the river, iron and manganese concentrations are generally lower. Emmett and Jeffery (1968) reported iron to vary between 0.29 and 5.1 mg/L, and manganese to vary from less than 0.05 mg/L to 4.4 mg/L. Total dissolved solids are generally 450 mg/L to 750 mg/L.

Groundwater pumped from bedrock sources in the Ozark and Springfield Plateau provinces requires very little treatment before consumption. In some instances, the water is chlorinated before being pumped into the water mains. The chlorination is sometimes necessary to control the growth of so-called iron bacteria in the mains. These bacteria are sulfate reducers whose by-products include hydrogen sulfide (H_2S) gas and "iron slime." However, groundwater produced from alluvium generally requires more extensive treatment before it can be used to supply a public water system. The alluvial water is more

directly influenced by surface water sources, which increases the risk of bacterial, viral, and other biologic contaminants. Treatment of municipal water supplies commonly includes iron and manganese removal, and some sort of softening, chlorination and retention. The cost of producing 1,000 gallons of alluvial groundwater for municipal use is usually at least twice as high as the same volume of bedrock groundwater.

GROUNDWATER CONTAMINATION POTENTIAL

The potential for groundwater contamination of the alluvial sediments in the Missouri River valley is similar to that of the Bootheel or the Mississippi River alluvium. Where the shallow alluvial materials are sandy and the vertical permeability is relatively high, it is possible for contaminants to rapidly find their way to the water table. This is particularly true of certain pesticides and fertilizers used in agricultural practices. It is also true that pumping of this aquifer will induce recharge from the river; a river whose water quality varies considerably.

Since the alluvial aquifer is so highly vulnerable to contamination, great care must be taken to assure that potential contaminant sources such as landfills, sewage lagoons, chemical storage areas and pipelines do not adversely affect the quality of the alluvial water.

NORTHWESTERN MISSOURI GROUNDWATER PROVINCE

INTRODUCTION

Groundwater resources are much less plentiful in the northern half of Missouri than in the Ozarks and Southeastern Lowlands. The bedrock units that yield large volumes of good quality water in the Salem and Springfield plateaus are also present in the northern part of the state, but are at a much greater depth and, except for the southern part of the Northeastern Missouri groundwater province, generally yield water too highly mineralized for most uses. The most widely used aquifer in the region is glacial drift, which is present throughout much of northern Missouri.

In this report, northern Missouri is divided into the Northwestern Missouri groundwater province and the Northeastern Missouri groundwater province. The dividing line between them is the county boundaries between Schuyler and Putnam, Adair and Sullivan, Macon and Linn, Randolph and Chariton, and Howard and Chariton counties. This division is based more on the availability of data than on changes in hydrogeologic conditions. A test-drilling program conducted in the 1950s in northwestern Missouri helped greatly to characterize the glacial drift and determine its groundwater possibilities. In northeastern Missouri, the glacial sediments are generally thinner and less permeable, and have less groundwater-production potential. However, the bedrock units in some parts of northeast Missouri are more likely to produce potable groundwater than those in the northwest part of the state.

GEOLOGY

Based on the divisions used in this report, the Northwestern Missouri groundwater province consists of 23 counties and covers an area of about 12,117 square miles. Much of the area is covered by thick Pleistocene-age (Ice Age) glacial sediments and recent alluvial deposits. These sediments overlie Pennsylvanian-age and older bedrock formations (table 13). Prior to the onset of glaciation, a mature topography of rolling hills and numerous valleys was developed throughout northern Missouri. There were streams draining surface-water runoff from the area, and surficial materials complete with soil profiles had developed from weathering of Pennsylvanian-age and older bedrock. However, the thick productive soils we know today were not present prior to glaciation.

Ice sheets advanced across northern Missouri at least twice during the Pleistocene, with the maximum southern extent of glaciation roughly paralleling the Missouri River (figure 58). As glaciers advanced across the northern part of the state, they carried a load of boulders, gravel, sand, silt and clay derived en route from areas to the north. The weight of the ice, coupled with the abrasive nature of the transported debris, altered the existing landscape to some extent. When the ice sheets melted and slowly withdrew from Missouri, they left behind deposits of glacial sediments locally thicker than 300 ft. Sediments were mostly deposited from melting continental glaciers at the end of the two ice

System	Series	Group or Formation	Lithology	Hydrology
Quaternary	Recent	Alluvium	Sand and gravel, with interbedded silt and clay deposited by stream action	Yields 30-500 gpm where sufficient thickness of saturated permeable sand and gravel is present
	Pleistocene	Glacial Till or Drift	Heterogeneous mixture of clay, silt, sand, gravel, and boulder-size material	3-50 gpm available to well where clean, permeable sand and gravel are present
		Preglacial valley fill	Sand and gravel, silt and clay intermixed. Stream-deposited material	Preglacial alluvium may yield as much as 500 gpm where saturated thickness and permeabilities allow
Pennsylvanian	Virgilian	Wabaunsee Group	Shale, siltstone & sandstone	Not considered to be water bearing. Very small quantities of water (1/2-1 gpm) may be obtained locally from the limestone sequences.
		Shawnee Group	Thick limestone formations with intervening shale beds	
		Douglas Group	Dominantly clastic formations. Shale, sandstone & thin limestone	
	Missourian	Pedee Group	A thick sequence of shale with limestone at the top	Small amounts of water (1-3 gpm) locally from thicker limestone formations
		Lansing Group	Two thick limestone sequences separated by shale & sandstone	
		Kansas City Group	Thick limestone formations with intervening shale, some sandstone beds, black, fissile shale in lower part.	Not generally water bearing
		Pleasanton Group	Thick shale sequence with sandstone in lower part. Few thin limestone beds and siltstones. Scattered coal beds	
	Desmoinesian	Marmaton Group	Shale, limestone, clay and coal beds	Small yields (1-3 gpm) of potable water at depths less than 100 feet in outcrop area.
		Cherokee Group	Sandstone, siltstone and shale	
Units older than Pennsylvanian typically yield highly mineralized water.				

Table 13. Geologic section of the Northwestern Missouri groundwater province.

advances into Missouri. These types of deposits, characteristically, have extremely variable lithologies and thicknesses. In some places, particularly where sediments were deposited in preglacial valleys and channels, the glacial materials are relatively clean, consisting mostly of sand and to a lesser degree gravel. Glacial sediments that were transported by melt water and deposited as stratified materials are often termed stratified drift. In other areas, the deposits are more heterogeneous and non-stratified. This

material is commonly called unstratified drift or glacial till. A more general term for all types of glacial deposits is simply glacial drift.

After glaciers retreated at the end of the Ice Age, most of the glaciated terrain exhibited an uneven land surface. Undoubtedly, there were very rugged areas as well as relatively flat areas. Post-glacial erosion and stream action has greatly modified the landscape since the glaciation ended. In some areas, erosion has completely removed the glacial

drift deposits, leaving Pennsylvanian bedrock at the surface.

The preglacial drainage system appears to have been well-developed and extensive. The Grand River, which today traverses the area from northwest to southeast, and enters the Missouri River in southwestern Chariton County, is thought to be the approximate path of the preglacial Missouri River. The movement of glaciers into midwestern North America rerouted the ancestral river, and moved it into its present channel along the northwestern edge of the state. Several other northwest Missouri streams were rerouted or covered by glacial ice. Prior to glaciation, all of these drainages had alluvial deposits underlying their floodplains, with the larger streams having more extensive alluvial deposits than the smaller ones. At the melting of the ice sheets at the end of the Ice Age, these drainage ways were filled with glacial drift or till. While some drainages, such as the ancestral Missouri River/Grand River, were partially reclaimed by later erosion, others have no surface expression that reveals their presence.

HYDROGEOLOGY

Groundwater resources in much of northwest Missouri are poor. The thick carbonate aquifers that supply large quantities of high-quality water in the Ozarks and east-central Missouri are also present at great depth in the northwestern part of the state. In northwest Missouri they yield water so highly mineralized that, for practical purposes, it is unusable. Bedrock formations in the Northwestern Missouri groundwater province older than Pennsylvanian-age yield highly-mineralized water. Usable quantities of groundwater are locally available from Pennsylvanian strata, but yields are typically low and the water quality is marginal. Glacial deposits, depending on thickness and texture, can yield from zero to more than 500 gpm. Except for the Missouri River alluvium, alluvial deposits in northwest Missouri generally yield small quantities of water. This is because the alluvial sediments of the smaller rivers are finer-grained and more poorly-sorted than those of

the Missouri River. However, there are significant exceptions to this, especially near the mouths of major northwest Missouri rivers where the alluvium may yield quantities of water suitable for irrigation or public water supply.

Many years ago, geologists recognized that the stratigraphy and geomorphology of this area are so complex and site specific that it is difficult to predict either the lithologic character or the thickness of material likely to be encountered at any drill site. So, in 1956, using funds provided by the Missouri Legislature, the Missouri Geological Survey (now the Division of Geology and Land Survey) began an ambitious test drilling program to determine the thickness and character of the glacial drift in the Northwestern Missouri groundwater province. The project, which ended in 1960, included 19 of the 23 counties in the province. These drilling studies did much to help northwest Missouri towns and rural residents develop safer, more reliable water supplies. The four northwestern Missouri counties excluded from detailed drilling studies were found not to contain appreciable thicknesses of permeable glacial drift materials. Limited funds prevented their study, as well as a similar study to cover the northeastern part of the state. Table 14 is a listing of county studies available for the area. The studies are a valuable aid to finding and developing water supplies. Groundwater storage estimates for northwest Missouri included with this report rely heavily on the data collected during the 1950s.

PRE-PENNSYLVANIAN AQUIFERS

Mississippian and older sedimentary rock units underlie the exposed Pennsylvanian strata and glacial drift in northwest Missouri. Data from relatively deep test holes, drilled primarily in search of oil, show that groundwater in rock older than Pennsylvanian-age in northwest Missouri is too highly mineralized for most uses. Total dissolved solids of groundwater from deeper bedrock aquifer zones range from about 2,000 mg/L to more than 30,000 mg/L.

WR-15	Andrew County	WR-08	DeKalb County	WR-06	Livingston County
WR-18	Atchison County	WR-07	Gentry County	WR-02	Mercer County
WR-14	Buchanan County	WR-01	Grundy County	WR-16	Nodaway County
WR-13	Carroll County	WR-03	Harrison County	WR-04	Putnam County
WR-12	Chariton County	WR-17	Holt County	WR-10	Sullivan County
*No. 19	Clay County	WR-11	Linn County	WR-05	Worth County
WR-09	Daviess County				

*No. 19 unpublished 1971 & 1972.

Table 14. Listing of county groundwater studies available for the Northwestern Missouri groundwater province.

PENNSYLVANIAN AQUIFER

Pennsylvanian-age bedrock consisting of relatively thin limestone, sandstone and shale units with occasional coal seams, underlies essentially all of northwest Missouri. The Pennsylvanian rocks are thinnest along the eastern margin of the province where they are 200 to 300 ft thick, and thicken greatly in the Forest City basin in extreme northwest Missouri where they are as much as 1,800 ft thick. The Pennsylvanian bedrock formations locally contain small amounts of marginally potable groundwater, but only at shallow depths. Despite the great thickness of Pennsylvanian-age rock in northwest Missouri, only the upper 100 to 150 ft potentially can yield potable water. Deeper Pennsylvanian units contain progressively more mineralized groundwater.

All of the Pennsylvanian units are typified by very poor vertical and horizontal permeabilities. Recharge to the Pennsylvanian rock from overlying glacial drift, as well as direct recharge from precipitation in areas where there is no drift, is also very poor. Thus, these deposits are not generally considered to be a viable source of groundwater. In addition, they also contain water which is of marginal quality. If a usable volume of water is encountered at a shallow depth, generally

less than 100 to 150 ft, it is far more likely to be of usable quality than groundwater at a greater depth. Locally, a few exceptions exist. For instance, there is an area in southern Clay County where an east-west trending channel sandstone of Pennsylvanian-age has historically yielded 10 to 20 gpm to water wells. This linear, localized formation, which is the Tonganoxie Sandstone Member of the Stranger Formation, was deposited in a relatively narrow trench or valley during Pennsylvanian time. The sandstone is directly overlain by permeable glacial drift. It appears that the overlying drift is providing recharge water to the sandstone from a relatively large recharge area, even though the areal extent of the sandstone is small. Locally, small springs are fed from the sandstone. The small community of Tiffany Springs derives its name from the small spring issuing from between bedding planes in the sandstone near the east end of the channel. Small quantities of crude oil concentrated near the margins of the sandstone body are also associated with the sandstone. Hydrostatic pressure within the sandstone body caused by the relatively constant recharge from the overlying glacial drift has kept the oil from migrating. If hydrologic conditions were to change, then the oil within the

formation boundaries could migrate into existing water wells. Such changes could occur if production of groundwater from the Tonganoxie were to increase to a point where it exceeds recharge, or if major construction such as that associated with large industrial development or highway construction, were to occur in the recharge area.

Table 15 shows groundwater quality in the Pennsylvanian at several locations in northwest Missouri. At best, groundwater in the shallower bedrock zones is marginal in quality, having total dissolved solids that range from 800 mg/L to about 2,000 mg/L. The water can also contain excessive sulfate, chloride, iron and manganese. Its use as a domestic water supply is warranted only because in many parts of the area, such as where the glacial drift is not water-bearing or is absent, there are simply no other options except a cistern or developing a surface-water supply. Water quality worsens with depth. The deeper Pennsylvanian bedrock formations contain groundwater with total dissolved solids that range between 2,000 mg/L and 30,000 mg/L or more.

GLACIAL DRIFT AQUIFER

The most widespread groundwater resources in northwest Missouri occur in the glacial materials. Depending on thickness, composition, and other factors, the glacial drift can yield from less than a gallon of water per minute, to as much as 500 gpm. Average yield of the glacial drift throughout northwest Missouri is probably less than 5 gpm.

The areas with the highest potential yields are drift-filled preglacial valleys where pre-Pleistocene alluvial deposits were covered with glacial drift. In places, the alluvial deposits found in these preglacial drainage systems yield from 100 to 500 gpm. These preglacial alluvial deposits are, unfortunately, limited in areal extent, and are found in rather narrow linear trends, much the same as modern alluvial valleys. Figure 61 shows the axes of major preglacial valleys known to exist in northwest Missouri. Figure 62 shows the thickness of clean sand found in the glacial drift. Clean sand contains little or no clay or silt, and at least a few feet of it is necessary for a successful small-diameter water-supply well. Drift-filled preglacial valleys can contain more

Well Owner	Well Location		Total Depth (Feet)	Date Of Collection	Water Quality															
	County	Location T R Sec.			Milligrams per liter															
					Silica (SO ₂)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃ -N)	Dissolved solids (Residue at 180 C)	Hardness as CaCO ₃		pH
																Calcium, magnesium	Noncarbonate			
Ralph Ecklles	Andrew	60N 35W 11	189	06-24-57	6.0	00.3	0.00	76	30	607		416	396	502	1.4	1.4	1,817	315	0	7.6
Rudolph Kruse	Carroll	53N 23W 16	495	05-08-57	6.5	03.4	0.05	322	158	3,324		469	1,073	5,000	1.4	0.1	10,277	392	1,061	7.4
Hugh Swords	Dekalb	58N 30W 28	425	11-20-56	5.3	03.8	0.17	96	47	1,632		452	216	2,348	0.6	6.2	4,589	389	33	8.2
Town of Ridgeway	Harrison	64N 27W 03	1,178	10-20-64	6.0	01.5	0.00	94	30	1,500	35	466	1,704	1,150	1.8	0.0	4,914	356	0	7.3
R. E. Dolan	Linn	58N 21W 05	565	02-05-57	5.5	03.4	0.05	84	46	2,397		418	988	3,060	1.4	0.1	6,787	391	6	7.6
Mercer Public School	Mercer	66N 23W 20	450	01-05-56	6.5	02.7	0.00	41	29	744		1,243	313	278	1.6	0.0	2,011	1,080	0	7.9
John Gaskill	Platte	54N 36W 13	460	04-07-51	4.0	30.0	--	84	40	3,757		347	39	5,747	---	---	9,768	284	89	7.6

Table 15. Groundwater quality data for selected Northwestern Missouri wells producing from Pennsylvanian strata (from Gann and others, 1973).

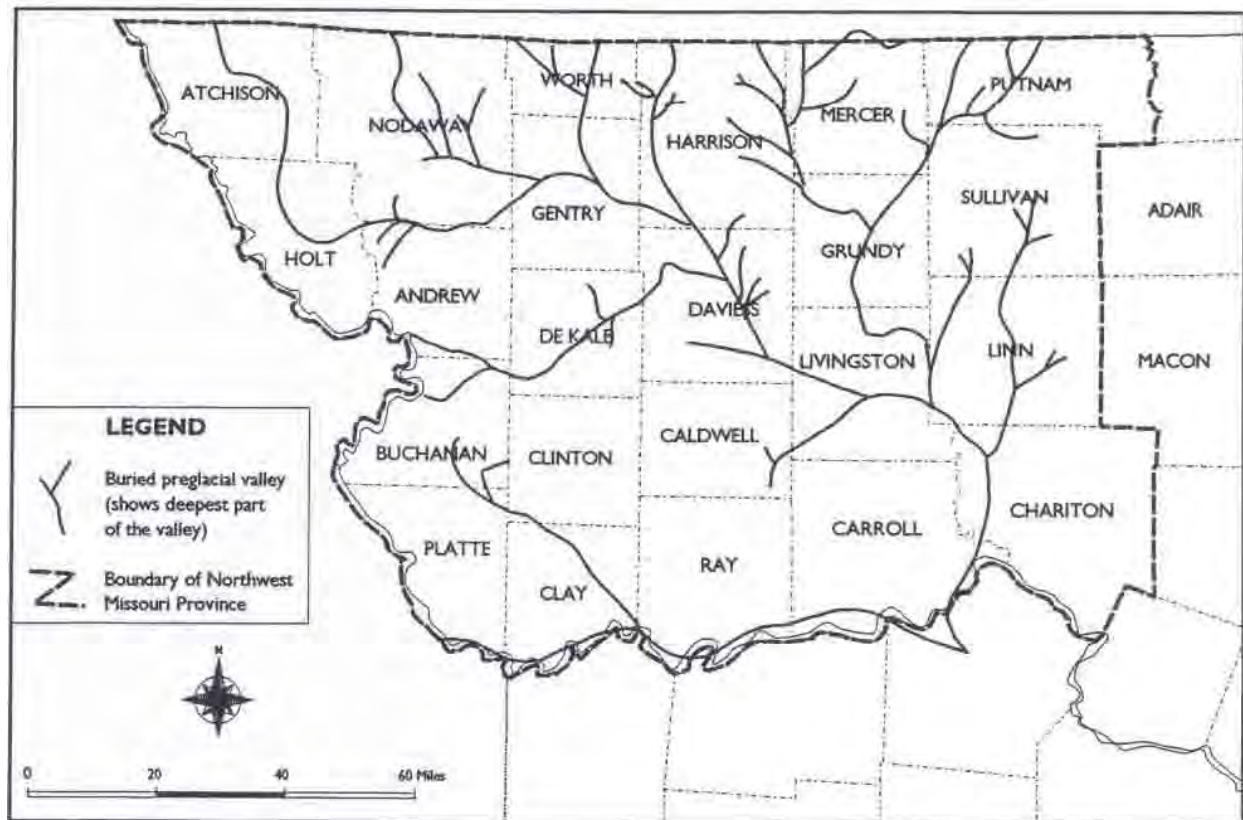


Figure 61. Pre-glacial drainage in the Northwestern Missouri groundwater province (from Gann and others, 1973).

than 100 ft of clean sand and gravel. The data used to produce figure 62 are incomplete because four counties in northwest Missouri were not included in the drilling program of the late 1950s. Supplemental data for these counties obtained from other sources were used in developing the illustration.

Preglacial valleys containing more than 100 ft of clean sand and gravel underlie an area of only about 922 mi², or about 7.6 percent of northwest Missouri. Assuming a saturated thickness of 150 ft, and a specific yield of 0.15, water stored in preglacial valleys of northwest Missouri is estimated to be about 4.33 trillion gallons, or about 13.3 million acre-feet.

A considerably larger area of the Northwestern Missouri groundwater province, about 2,786 mi² or 23 percent of the province, is underlain by glacial deposits consisting of 25

to 100 ft of clean sand. Water production from these materials is generally much less than from drift-filled preglacial valleys, but yields of 10 to 25 gpm are possible. Based on an assumed saturated thickness of 62.5 ft and a specific yield of 0.1, the volume of water stored in this part of the glacial drift aquifer of the Northwestern Missouri groundwater province is estimated to be about 3.63 trillion gallons, or about 11.1 million acre-feet.

Almost 62 percent of the Northwestern Missouri groundwater province, an area containing about 7,511 mi², either contains no glacial drift, or is underlain by drift containing less than 25 ft of clean sand. Assuming a saturated thickness of 12.5 ft and a specific yield of 0.05, there is approximately 0.84 trillion gallons or 2.6 million acre-feet of groundwater in this part of the aquifer.

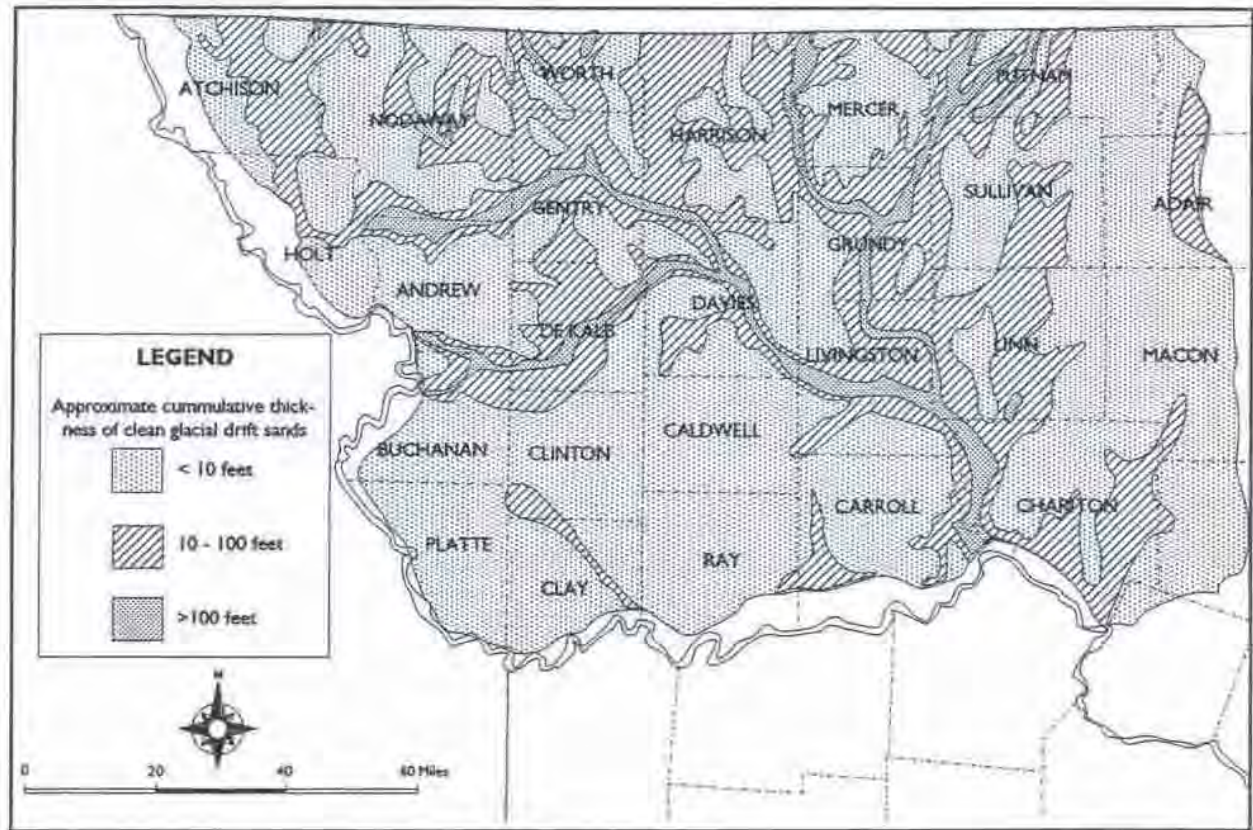


Figure 62. Groundwater possibilities of the glacial drift in the Northwestern Missouri groundwater province (from Gann and others, 1973).

The total volume of groundwater contained in the glacial drift aquifer of the Northwestern Missouri groundwater province is estimated to be 8.80 trillion gallons, or 27 million acre-feet.

The glacial drift of the Northwestern Missouri groundwater province is a complex geologic deposit that can vary in thickness and texture over relatively short distances. It is often necessary to drill several test holes to locate the most water-productive materials at a particular site. It is not unusual to find pockets or lenses of permeable material that are completely surrounded by nearly impermeable clay or silt. The lenses may contain water, but due to limited recharge through the impermeable material, do not have good sustained-yield characteristics. Typically, where the drift is thickest, the probability of encoun-

tering sufficient thicknesses of permeable material is best. In many instances, the yield of a well is greatly controlled by the type of well construction used. Yields of conventional wells drilled into glacial drift ranges from a few gallons a minute to 50 gpm, depending on the thickness of clean or permeable sand and gravel. In areas where the thickness or the permeability of the drift is low, large-diameter dug or augered wells are commonly used as water sources. These wells commonly range from two to more than four feet across. Their large diameters provide more inflow area in the permeable zones and increases the storage capacity within the well bore. Their shallow depth and the general lack of effective sealant around the casing or lining makes them more susceptible to contamination than conventional drilled wells.

Overlying the glacial drift, and in some places the Pennsylvanian bedrock formations, is a blanket of silt- and clay-sized material called loess. The loess, which is wind-blown silt, was derived from river floodplains during interglacial periods of the Quaternary. It is usually thickest atop the bluffs and uplands overlooking the major rivers, and thins away from the major river valleys. Being a silt, the loess is moderately permeable. However, since it occupies a high topographic setting, it is typically well drained and generally does not contain appreciable groundwater.

Direction of groundwater flow in the shallow glacial sediments is a factor that is controlled by the present-day surface topography, and the direction of flow in the deeper glacial sediments is controlled, to a great extent, by the preglacial topography impressed on the Pennsylvanian bedrock beneath the drift. Since the character of these deposits is not uniform and permeable, water-bearing zones may be perched or isolated within impermeable zones. Rates of flow within any section of glacial material are generally very slow.

The quality of groundwater contained in glacial drift deposits in northwest Missouri tends to be much better than that in the underlying bedrock, even though recharge and circulation rates are fairly low. Total dissolved solids range between 400 and 1,500 mg/L (Gann and others, 1973). Groundwater quality in the buried, preglacial channels tends to be of poorer quality. This is due to the longer residence time of water in the channel, poor recharge potential, and local leakage of water from adjacent or deeper bedrock formations that contain highly mineralized water.

RECENT ALLUVIUM

The Missouri River alluvium, previously addressed in this report, is the most important alluvial aquifer in northwest Missouri. Alluvial deposits beneath the floodplains of other major streams and their tributaries in northwest Missouri tend to be finer-grained and much less permeable than the Missouri River alluvium. In addition, the alluvial sediments

also tend to become progressively finer-grained as the distance from the mouth of the river increases, particularly along smaller tributary streams. The reason for this noticeable difference in the texture of the alluvium is the source area for the alluvial material. The alluvial sediments of northwest Missouri stream valleys were derived from the weathering of the glacial drift. Since the shallow glacial sediments are predominately clay, silt and fine sand, the eroded material transported into the tributary streams tends to be fine-grained. The thickness of the alluvial material in the major streams in this region ranges from only a few feet in headwater reaches and along smaller tributary valleys to approximately 60 ft in the southern part of the region. The saturated thickness of the material is somewhat less, ranging from less than 10 ft in the north to about 45 ft in the south.

There are records for relatively few wells or test holes that penetrate the alluvium of most northwest Missouri rivers. In general, the most favorable alluvial deposits appear to be those of the lower parts of the Grand and Chariton rivers. The Chariton River alluvium along its lower reach is known to be a good aquifer. In 1980, the city of Salisbury in Chariton County abandoned its former alluvial well supply on the Middle Fork of the Chariton River east of the town, and developed a new well field in the Chariton River alluvium about 4 miles to the west. Aside from developing a surface-water supply, the only other feasible long-term alternative was to develop a well field in the Missouri River alluvium that would have required at least 10 to 12 miles of pipeline. A 24-hour pumping test of the first Salisbury production well drilled in the Chariton River alluvium showed that it was capable of yielding more than 400 gpm. Drawdowns measured at five observation wells showed the transmissivity of the alluvium to be about 34,000 gpd/ft (4,550 ft²/day), and its storage coefficient to range between about 1.6×10^{-3} and 3×10^{-4} . The city subsequently installed three production wells that have performed quite well for the past 16 years.

Existing information is not adequate to establish the water-producing characteristics of the alluvial deposits of most northwest Missouri streams, or accurately estimate the volume of groundwater stored in the deposits. The Grand, Thompson, Chariton, Platte and Nodaway rivers are known to have sufficient alluvial deposits to yield at least 50 gpm. Test drilling would be necessary to determine if other streams had similar potential. Figure 63 shows the major alluvial deposits of the Northwestern Missouri groundwater province. The volume of groundwater stored in alluvium along these rivers is conservatively estimated to be about 385 billion gallons, or about 1.2 million acre-ft, but could easily be several times more.

The chemistry of the groundwater in the alluvial deposits along the major rivers and tributaries of northwest Missouri is similar to the chemistry of water from the alluvium of

the Missouri River. However, iron and manganese levels tend to be even higher in the alluvium of the Missouri River tributaries, ranging between 0.4 mg/L to 18.0 mg/L for iron, and 0.3 mg/L to 1.8 mg/L for manganese, with the averages being 5.0 mg/L and 0.35 mg/L respectively. Total dissolved solids range from a low of 230 mg/L to a high of approximately 850 mg/L (Gann and others, 1973).

GROUNDWATER CONTAMINATION POTENTIAL

In the Northwestern Missouri groundwater province, groundwater recharge rates and groundwater velocities are relatively low, both in the unconsolidated and bedrock aquifers. Groundwater contamination is possible, and numerous cases of groundwater pollution have been documented. However, most are local problems caused by private septic systems, agricultural runoff from livestock con-

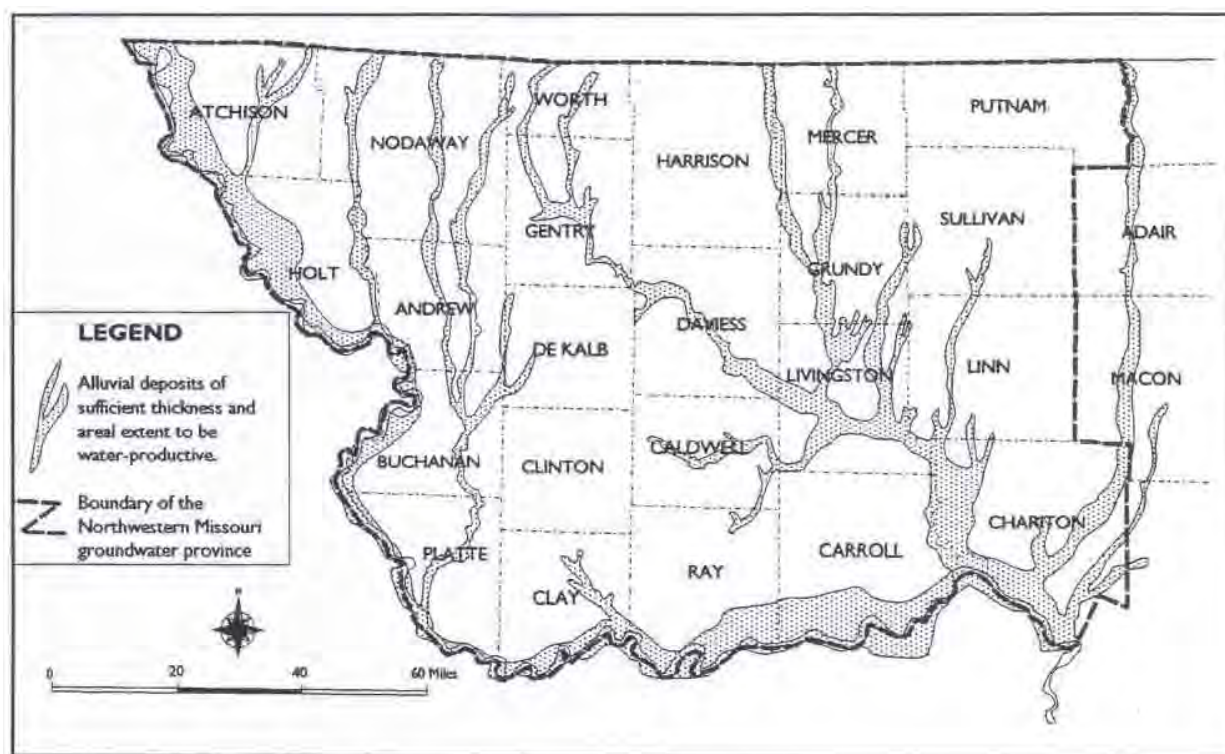


Figure 63. Major alluvial deposits in the Northwestern Missouri groundwater province (from Gann and others, 1973).

finements, fertilizer, and other agricultural chemicals such as pesticides and herbicides.

Municipal wastewater stabilization lagoons are also local risks to groundwater resources. Any waste-disposal facility should be carefully sited. Even though water resources are meager in much of the region, glacial drift water is often all that is available for rural use.

The wells at greatest risk to groundwater contamination are shallow wells in the upper part of the glacial drift. Prior to the availability of modern drilling machines, these shallow glacial drift wells were dug by hand. They are generally less than 30 ft deep, 3 to 6 ft in diameter, and typically lined with field stones or brick. These wells were and are still used in areas where the glacial drift contains little clean sand and production is low. Their large

diameters allow them to collect and store a substantial volume of water, despite a low inflow rate. However, these wells are difficult to seal, and are open to very shallow horizons. Thus, they routinely contain bacteria and, where affected by agricultural runoff, may contain excessive nitrate and agricultural chemicals. The modern equivalent of the hand-dug well is drilled with a large auger or bucket-type drilling rig. The new wells can be cased with tile or concrete casing that can be more effectively sealed, which helps reduce the chances of shallow contaminants entering the well bore. Properly constructed drilled wells that are cased with steel or plastic casing and produce from deeper horizons in thick drift deposits are not normally affected by shallow contaminants.

NORTHEASTERN MISSOURI GROUNDWATER PROVINCE

INTRODUCTION

This province includes all or parts of 21 counties, and encompasses an area of about 11,708 mi². It is bounded to the north by the Missouri-Iowa border, on the east by the Mississippi River, on the south by the Missouri River, on the west by the Northwestern Missouri groundwater province.

This area shares several geologic similarities with the Northwestern Missouri groundwater province. It contains glacial drift deposits that are underlain by Pennsylvanian and older bedrock. However, groundwater conditions in the Northeastern Missouri groundwater province are considerably more diverse than those in northwest Missouri. Because of this diversity, northeastern Missouri is probably the most difficult of the groundwater provinces to accurately characterize.

In the northern and western part of the Northeastern Missouri groundwater province, the glacial drift is moderately thick, but generally has a very low permeability. It normally can supply water only in small quantities. It is underlain by Pennsylvanian strata which, like strata in northwest Missouri, generally yield only small quantities of poor quality water. The eastern part of the province also contains glacial drift, but it is generally thinner than to the north and west. Here, the drift is directly underlain by Mississippian-age bedrock that, in its upper part, can yield moderate quantities of potable water. Farther to the south along the Mississippi River, uplift along the Lincoln Fold has brought older, early Mississippian,

Devonian, and Ordovician rocks to the surface. Yields and water quality vary greatly in these deposits. The southern part of the province, from northern Audrain County to the Missouri River, is also underlain by glacial drift, but here it is of little importance as an aquifer. The freshwater-salinewater transition zone crosses the province along northern Audrain County, and south of the transition zone aquifers in Mississippian, Ordovician, and Cambrian bedrock units yield large quantities of good quality water.

GEOLOGY

Bedrock units underlying the Northeastern Missouri groundwater province that are hydrologically significant range in age from Cambrian to Pennsylvanian (table 16). The lithologies of most of these geologic units have been discussed in other sections of the report, and will not be described in detail here. The Cambrian strata that form the St. Francois aquifer in the Ozarks are present at considerable depth in northeast Missouri, and south of the freshwater-salinewater transition zone are likely to contain potable water. However, they are not known to be currently used in this area. The Davis Formation, which forms the St. Francois aquifer confining unit to the south, is also present and serves the same hydrologic function in northeast Missouri that it does in the Ozarks—it hydrologically separates the shallower water-bearing strata above the Davis from the deeper Bonnetterre Formation and Lamotte Sandstone. The clastic part

System	Series	Group or Formation	Lithology	Hydrology	
Quaternary	Recent	Alluvium	Clay, silt, sand and gravel. Stream deposits	Yields 25 to 100 gpm where there is sufficient thickness of "clean" saturated sand and gravel.	
	Pleistocene	Glacial Till or Drift	Silty, clay, sand, gravel and boulders. May be bedded or indeterminant mixture. Deposited by melting glaciers.	Yields 5 to 275 gpm are possible where sufficient thickness of "clean" saturated sand and gravel is present.	
Pennsylvanian	Missourian	Pleasanton Group	Dominantly clastic sediments. Shale, siltstone and scattered sandstone beds	Not water bearing except where sandstone channels occur, then yields of 3 to 4 gpm are possible.	
	Desmoinesian	Marmaton Group	Shale, limestone, clay and coal beds	Not utilized as a source of groundwater in this province.	
		Cherokee Group	Sandstone, siltstone, shale, underclay, coal and thin limestone beds. Recognizable cyclic sequences		
		Krebs Subgroup	Sandstone, siltstone, shale, clay, thin limestones. Some coal beds in shale sequences. Beds of conglomerate locally.		
Mississippian	Meramecian	St. Genevieve Limestone St. Louis Limestone	Fine- to medium-crystalline limestone and shale	May yield 5-10 gpm where units are not deeply buried. Water is mineralized when found below 300 feet.	
		Salem Formation	Buff-colored limestone, dolomitic limestone and shale		
		Warsaw Formation	Fine- to coarsely-crystalline limestone		
	Osagean	Keokuk Limestone	Bluish gray, medium- to coarsely-crystalline, medium-bedded limestone. Abundant light-gray chert.	May yield 10-15 gpm of potable water near the outcrop line. Water is mineralized where formation is deeply buried.	
		Burlington Limestone	White to tan, coarsely-crystalline, fossiliferous limestone with layered chert nodules.		
	Rock units below the base of the Burlington Limestone contain mineralized water north of freshwater/salinewater transition zone.				
	Kinderhookian	Sedalia Limestone Chouteau Limestone	Limestone, dolomite, and shale	Confining layer throughout much of northern Missouri, thinning to the south.	
		Hannibal Shale	Shale		
Devonian	Upper	Louisiana Limestone Grassy Creek Shale Snyder Creek Shale	Shale and limestone	Unimportant as an aquifer.	
	Middle	Cedar Valley Limestone	Limestone		
	Lower				
Silurian		Bowling Green Dolomite	Limestone and dolomite		

Table 16. Stratigraphic section of the Northeastern Missouri groundwater province. (Modified from Imes, 1985.)

Table 16 continued

System	Series	Group or Formation	Lithology	Hydrology
Ordovician	Cincinnatian	Maquoketa Shale	Shale	Confining layer in extreme east along Mississippi River.
	Mohawkian	Kimmswick Limestone	Dolomite and limestone	Yields generally sufficient for domestic supplies. 5-10 gpm.
		Decorah Group Plattin Limestone Joachim Dolomite	Dolomite, limestone and shale	Limited source of water. Locally may be confining layers.
		St. Peter Sandstone	Sandstone and dolomite	Good production for domestic, farm and small industry. Excessively mineralized in the north. 25-75 gpm.
	Whiterockian			
Ordovician	Canadian	"Powell" Dolomite Cotter Dolomite Jefferson City Dolomite	Dolomite	Unimportant as an aquifer, but may produce sufficient water locally for domestic and farm use. 0-25 gpm.
		Roubidoux Formation	Sandstone and dolomite	Good producer. Commonly sufficient for municipal, industrial and irrigation water supplies. 50-500 gpm.
		Gasconade Dolomite Gunter Sandstone Mbr.	Dolomite and sandstone	
		Eminence Dolomite Potosi Dolomite	Dolomite	Excellent producer. Capable of large yields for large cities, industry and irrigation. 440-1,100 gpm.
Cambrian	Croixian	Derby-Doe Run Dolomites Davis Formation	Shale and dolomite	Limited source of water. Confining layer in northern Missouri.
		Bonnetterre Dolomite Lamotte Sandstone	Sandstone and dolomite	Little information available. Probably some production from the Lamotte sandstone.
Precambrian			Igneous rocks	Unimportant as a source of water.

of this sequence, which includes the Lamotte Sandstone in most of the province, and the Mt. Simon Sandstone in the northeast corner of the state, thickens from about 100 ft in the western part of the province to about 450 ft along the Mississippi River, but thins somewhat across the Lincoln Fold.

As in the Ozarks, the Davis is overlain by a thick sequence of Upper Cambrian and Ordovician formations that comprise the most significant bedrock aquifer in northeast Missouri. These include, in ascending order, the Derby-Doerun Dolomite, Potosi Dolomite and Eminence Dolomite, all of Cambrian age, and the Gasconade Dolomite, Roubidoux Formation, Jefferson City Dolomite, Cotter Dolomite, "Powell" Dolomite, Everton Forma-

tion, St. Peter Sandstone, Joachim Dolomite, Plattin Limestone, Decorah Group, and Kimmswick Limestone, all of Ordovician age. These units have a combined thickness that varies from about 900 ft in northeast Callaway County, to about 1,800 ft in central St. Charles County. Average thickness across most of the area of these units is about 1,300 ft.

The Maquoketa Shale is present in the eastern and southeastern part of the province where it can be as much as 140 ft thick. Silurian- and Devonian-age strata, including the Louisiana Limestone, Grassy Creek Shale, Saverton Shale, Snyder Creek Shale, and several other units are found in northeast Missouri. The combined thickness of these units range in thickness from zero in their outcrop areas

along the southern margin of the province and along the Lincoln Fold, to a maximum of about 320 ft in the northwestern corner of the province.

Many of the Mississippian-age formations that comprise the Springfield Plateau aquifer in southwest Missouri are also present in northeast Missouri. However, there are several other formations present in northeast Missouri that are not found in the southwestern part of the state. The lowermost Mississippian unit is the Hannibal Shale in the Kinderhookian Series. It is overlain by the Chouteau Group (undifferentiated) and Sedalia Formation, a predominately limestone sequence. Osagean Series formations include the Fern Glen, Burlington, and Keokuk limestones. These are overlain by Meramecian Series units that include, in ascending order, the Warsaw, Salem, St. Louis, and Ste. Genevieve limestones. As their names indicate, most of the Mississippian-age formations are predominately limestone units. The thickness of the Mississippian-age rock units vary greatly in the province. The Mississippian units are missing where they have been removed by erosion along the Lincoln Fold, and in the southern part of the province where older rock units form the bedrock surface. They generally increase in thickness to the northwest to a maximum of about 500 ft in Schuyler County, and to the southeast in extreme eastern St. Charles County to about 900 ft. Throughout most of the province, they average between 200 and 400 ft thick.

The western and most of the southern part of the province are underlain by bedrock of Pennsylvanian-age. These units are predominately fine-grained clastics and thin limestones interspersed with numerous coal seams. The formations are mostly in the Desmoinesian and Missourian Series, and include formations in the Krebs Subgroup, Cherokee Group, Marmaton Group, and Pleasanton Group. Total thickness of the Pennsylvanian sediments range from zero, where they have been removed by erosion at the edge of their outcrop belts along the Missouri River, to a maximum of about 300 ft in western Adair County. The

Pennsylvanian strata are missing in a large area of the eastern part of the province, mostly across the Lincoln Fold, but also to the north and west of it. In these areas, glacial drift directly overlies Mississippian-age and older strata.

There is a linear, east-west trending, geologically ancient channel eroded into Pennsylvanian rocks that trends easterly from southeastern Chariton County, through central Randolph County (including Moberly), and ends in east-central Monroe County. This channel, which is about 40 miles long and varies from less than one to as much as six miles wide, is filled with Pennsylvanian-age sandstone that is locally as much as 150 ft thick. This unit is stratigraphically equivalent to the Warrensburg Sandstone Member of the Pleasanton Formation to the southwest, but in northeast Missouri it is referred to as the Moberly Sandstone.

Like in northwest Missouri, glacial sediments of Pleistocene age overlie the bedrock formations throughout much of this province. These include glacial drift and loess, which range in thickness from 50 feet or less in the southern and southeastern part of the province to more than 300 feet in the extreme northwestern part (figure 64). In particular, the drift in the northern part of the northeast Missouri province has a greater percentage of coarse sand and gravel than that further to the south. However, despite the greater percentage of coarse clastics, most of the glacial drift deposits do not seem to be well sorted in zones. With few exceptions, the deposits are interspersed with clay and silt, leaving very little clean sand or gravel. The lithologic character of the glacial drift in northeastern Missouri is quite similar to that of the drift of northwestern Missouri. It consists mostly of clay and silt with lesser amounts of sand. It is probable that, like drift in the northwestern part of the state, it is a combination of material from multiple advances of the ice sheets into northern Missouri during both the Nebraskan and Kansan stages. This is undoubtedly true for the drift in the northern parts of both the Northwestern Missouri and Northeastern

Missouri groundwater provinces, where the drift is thickest. In many areas where drillhole information is available, geologists have observed weathered intervals within the drift, which show the development, or partial development, of an ancient soil zone. Ancient soil zones, termed paleosols or geosols, indicate major breaks in deposition that allow the newly deposited materials to be exposed to weathering.

Unlike the Northwestern Missouri groundwater province, where an extensive test-hole drilling program in the 1950s and 1960s characterized the glacial drift, the glacial deposits in northeast Missouri have never been explored through a detailed drilling program. Most of the information concerning the geologic and hydrologic characteristics of the glacial drift in the Northeast Missouri groundwater province is the result of water well

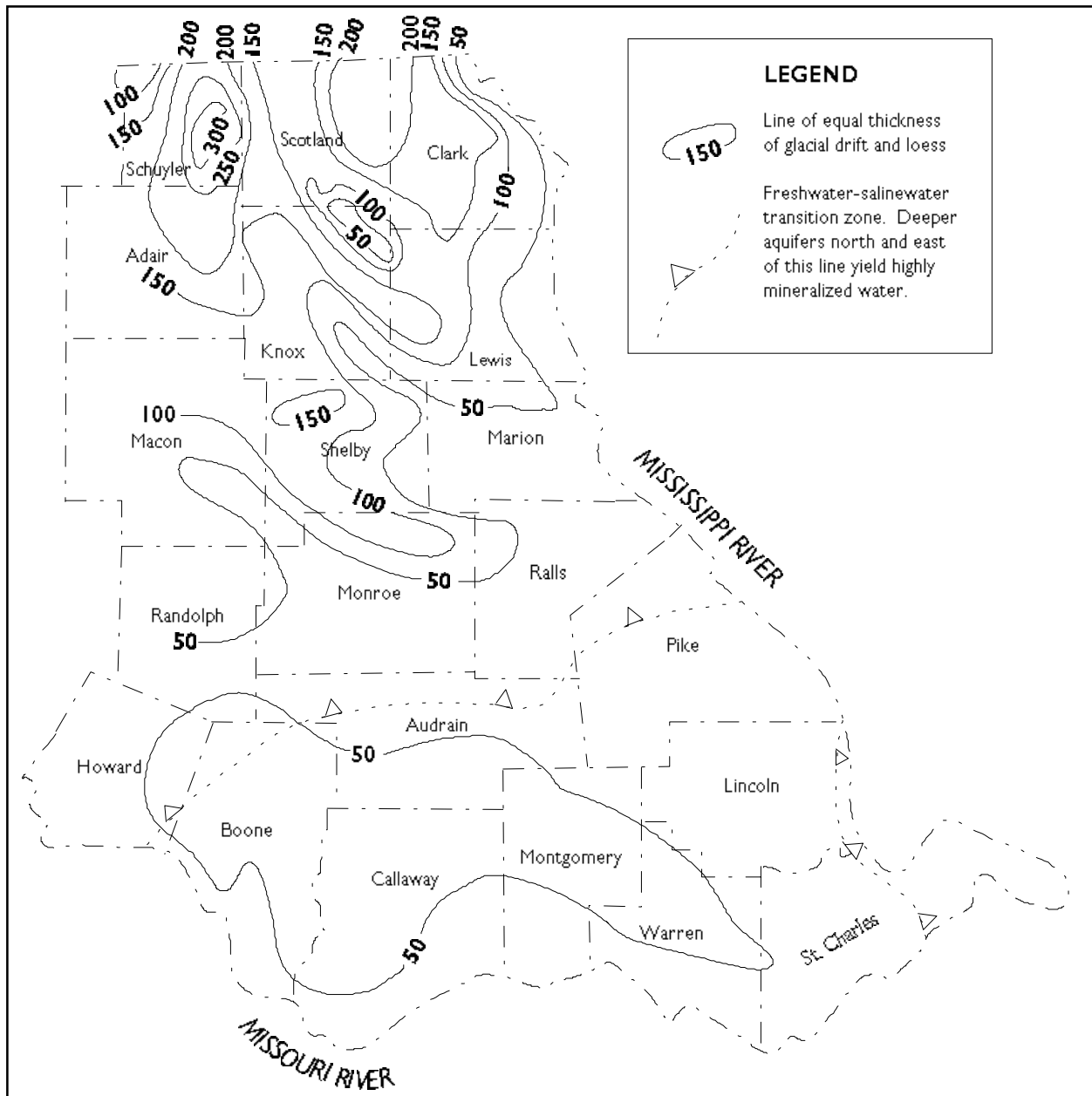


Figure 64. Thickness of glacial drift and loess in the Northeastern Missouri groundwater province (modified from Gann and others, 1971).

drillers submitting samples of well cuttings that were collected while wells were being drilled. The cuttings were subsequently examined by geologists at the Division of Geology and Land Survey and its predecessor, the Missouri Geological Survey. However, the vast majority of the glacial drift wells were hand dug several generations ago, and no information exists for most of them. Since the Northeastern Missouri groundwater province never received an extensive drilling program, there are little data to show the locations of preglacial drainage, or drift-filled channels, or even where the drift is more suitable for well development. A great deal more study is needed in dating and typifying the drift deposits to determine age, lithology and water-bearing character of the individual units.

HYDROGEOLOGY

Approximately the northern two-thirds of this province lies north of the freshwater-salinewater transition zone, which trends through western and northern Boone County, northern Audrain County, and central Pike County. South of the transition zone, wells drilled into the Mississippian-age rock generally yield enough water for domestic and farm purposes while wells penetrating the Ordovician and Upper Cambrian strata can yield quantities of water ample for irrigation, municipal and rural public water supply. North of the transition zone, the deeper bedrock water is highly mineralized, and without extensive treatment be used for potable water supply. Modest quantities of water can be produced from the Mississippian- and Pennsylvanian-age rock and the glacial drift, but water quality is generally marginal to poor. Up to a few miles north of the transition zone, the St. Peter Sandstone can yield potable water.

CAMBRIAN-ORDOVICIAN AQUIFER

The same bedrock units that comprise the Ozark aquifer in the Salem and Springfield plateaus are present in northeast Missouri, and also form its most significant bedrock aquifer. However, in this province it is referred to as the Cambrian-Ordovician aquifer, and it in-

cludes the bedrock sequence from the top of the Kimmswick Limestone to the base of the Derby-Doerun Dolomite. The reason for the different aquifer name is that it is not part of the Ozark aquifer flow system. The Ozark aquifer is recharged from precipitation in the Salem Plateau. Groundwater moves radially from the center of the Ozark Uplift, and at the northern boundary of the aquifer discharges into the Missouri River. The Cambrian-Ordovician aquifer appears to be recharged from north of the Missouri River. Imes (1985), using water-level data collected from wells drilled both for water supply and oil exploration, determined that there are two nearly independent flow systems within the Cambrian-Ordovician aquifer in north central and northeast Missouri. Potentiometric data shows saline water entering Missouri from the northwest. There is a groundwater divide in the vicinity of Linn, Chariton and Macon counties; part of the salinewater flows to the east beneath the Mississippi River into Illinois north of Lincoln County, and part flows to the south and discharges into the Missouri River in southern Chariton and Howard counties.

A local freshwater flow system is present in the southern part of the province in Boone, Audrain, southern Pike, Lincoln, St. Charles, Warren, Montgomery and Callaway counties. This freshwater flow system is recharged principally by downward movement of groundwater from the overlying Mississippian strata in southwestern Audrain and northern Warren counties, and by precipitation infiltration where the aquifer crops out along the southern margin of the province and atop the southern end of the Lincoln Fold (Imes, 1985).

The thickness of the Cambrian-Ordovician aquifer in the province, which includes the bedrock units between the base of the Maquoketa Shale and the top of the Davis Formation, varies from about 900 ft in northwest Callaway County to about 1,800 ft in central St. Charles County. Significant water-yielding units in the aquifer include the St. Peter Sandstone, Roubidoux Formation, lower Gasconade Dolomite, Gunter Sandstone Member, Eminence Dolomite, and Potosi

Dolomite. The part of the aquifer comprised by the Jefferson City, Cotter and "Powell" dolomites will yield enough water to provide for farm and domestic use, but typically not enough for high-yield demands. The Joachim Dolomite, Platin Limestone, and Decorah Group yield little water, and probably serve as local aquitards, but the overlying Kimmswick Limestone can yield enough water for domestic water supply.

Wells fully penetrating the Cambrian-Ordovician aquifer in the freshwater area can yield from 300 to more than 1,000 gpm. Short term pumping tests of these wells show that transmissivity of the aquifer varies greatly with respect to geographic location and the part of the aquifer open to the well. Values of from 3,500 gpd/ft (467 ft²/day) to more than 10,000 gpd/ft (1,337 ft²/day) have been calculated from pumping test data.

Regional groundwater modeling by Imes (1985) indicates that transmissivity of the freshwater part of the aquifer ranges from about 2,000 gpd/ft (267 ft²/day) to about 7,000 gpd/ft (935 ft²/day). Groundwater storage estimates indicate that the freshwater part of the Cambrian-Ordovician aquifer contains about 60.3 trillion gallons, or about 185 million acre-ft of water in storage.

Water quality is very poor in the Cambrian-Ordovician aquifer on the salinewater side of the freshwater-salinewater transition zone where total dissolved solids can exceed 10,000 mg/L. Throughout the freshwater part of the aquifer, dissolved solids are generally less than 1,000 mg/L. On the freshwater side, the water is a moderately mineralized calcium-magnesium-bicarbonate type. Sulfate and chloride are each typically below 250 mg/L. In the salinewater zones, the water is generally a sodium chloride type. Chloride can exceed 5,000 mg/L and sulfate can be more than 1,000 mg/L.

MISSISSIPPIAN-DEVONIAN-SILURIAN CONFINING UNIT

A thick sequence of low-permeability sedimentary rocks greatly impedes the ex-

change of water between the Cambrian-Ordovician aquifer and the shallower Mississippian aquifer. This aquitard is composed of several Lower Mississippian, Devonian and Silurian formations. The least permeable units include the Hannibal (or Kinderhook) Shale, Bachelor Formation, Grassy Creek Shale and Snyder Creek Shale. These strata are as much as 300 ft thick in extreme northeastern Missouri, and thin to a few feet or less in the southern counties of the province. These units are absent across the crest of the Lincoln Fold; here, the middle Ordovician Maquoketa Shale serves as the upper confining unit of the Cambrian-Ordovician aquifer.

MISSISSIPPIAN AQUIFER

Water-productive horizons in Mississippian strata can supply modest quantities of usable quality groundwater in some of the eastern and southern parts of the the Northeastern Missouri groundwater province. North of the freshwater-salinewater transition zone, those areas where the Pennsylvanian strata are thin or missing, and the glacial drift is relatively thin, have the best potential for yielding potable water. The most productive water-bearing zones are the Burlington-Keokuk limestones, and to a lesser extent the Sedalia and Chouteau limestones. Wells designed to take advantage of this aquifer should not be drilled any deeper than necessary. If a usable quantity of satisfactory quality water is not encountered in the upper 50 ft or so of the Mississippian strata, then it probably will not be found. Yields typically range from 5 to 15 gpm. Yields are generally less where the upper part of the Mississippian consists of Ste. Genevieve, St. Louis, and Salem limestones or Warsaw Formation. These units are typically less permeable than Burlington-Keokuk. Figure 65 shows the approximate area where Mississippian-age rock subcrops beneath the glacial drift.

South of the freshwater-salinewater transition zone, the Mississippian strata generally yields good-quality water. Yields increase somewhat since wells can take advantage of the full saturated thickness of the Mississippian strata and not just the upper part of it. Still,

yields of less than 15 gpm are still a realistic expectation.

It is difficult to estimate the volume of potable water available from the Mississippian aquifer in this province. Storage estimates north of the freshwater-salinewater transition zone assume that potable water is available from only that part of the Mississippian that subcrops directly below the glacial drift, that only the upper 50 ft of the Mississippian contains potable water, and that the specific

yield of the aquifer is 0.05. Storage estimates for counties south of the transition zone assume that the full saturated thickness of the Mississippian contains potable water, and that the specific yield of the aquifer is 0.05. Based on these assumptions, the Mississippian aquifer in the Northeastern Missouri groundwater province contains about 6.04 trillion gallons, or about 18.5 million acre-ft, of potable groundwater. Twenty-five percent of this, 1.52 trillion gallons or 4.67 million acre-ft, is

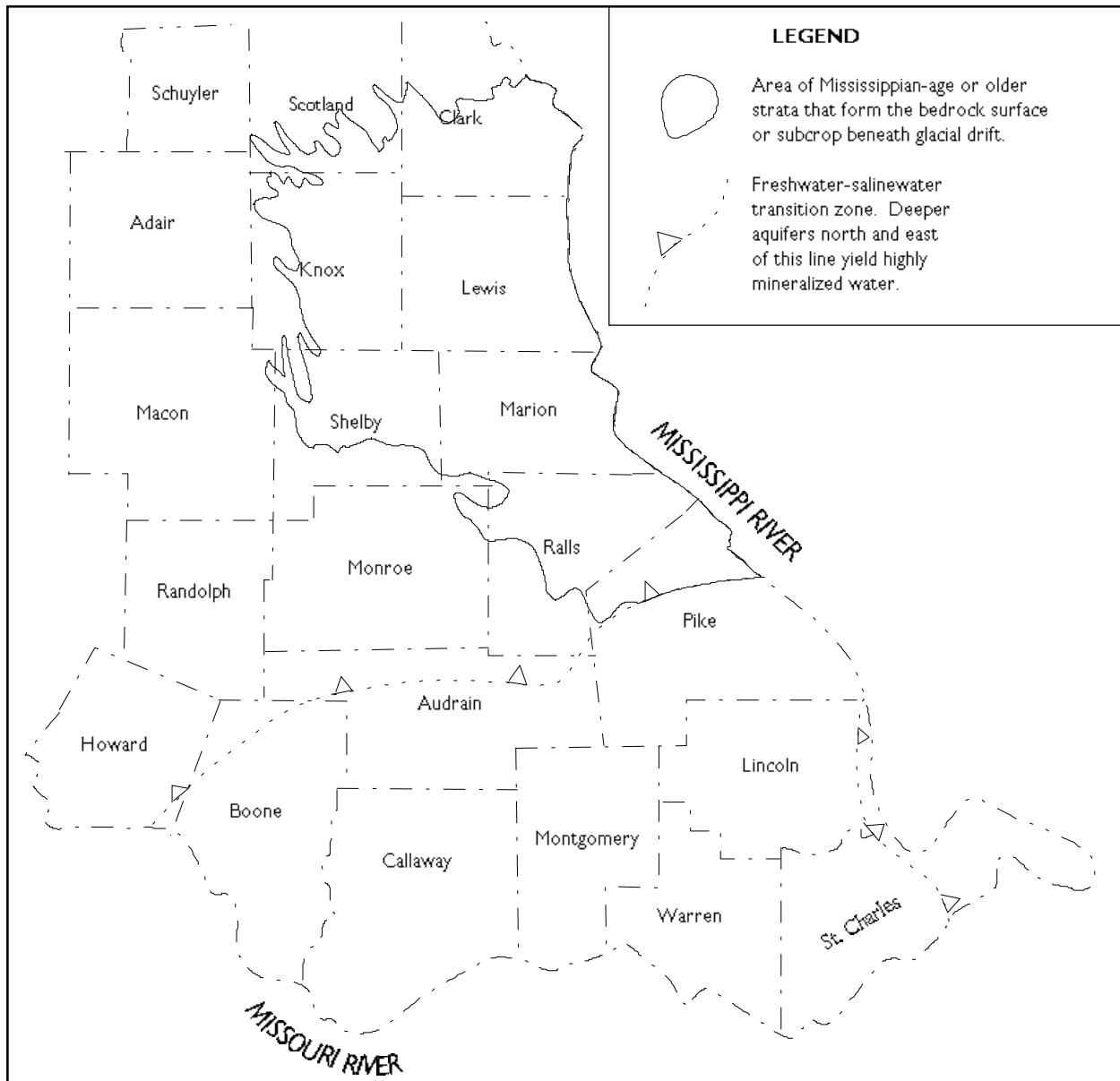


Figure 65. Area in northeast Missouri where Mississippian-age or older strata form the bedrock surface or subcrop beneath glacial drift.

contained in the aquifer north of the freshwater-salinewater transition zone, and the remaining 75 percent, 4.52 trillion gallons or 13.9 million acre-ft, is stored south of the transition zone.

A potentiometric map constructed by Imes (1985) shows a major groundwater divide in the Mississippian aquifer that extends from the Iowa line through central and eastern Schuyler and Adair counties, western Knox, Shelby, Monroe, Audrain and Callaway counties. West of the divide, groundwater in the Mississippian aquifer moves to the southwest toward the Missouri River. East of the divide, movement is toward the Mississippi River in the northern area and toward the Salt River in southern Shelby, Monroe, Ralls and northern Audrain counties. Mississippian aquifer water southwest of a groundwater high in southwest Audrain County flows toward the Missouri River. To the northeast and southeast of the high, groundwater in the Mississippian aquifer moves toward the Salt River, or toward the Missouri River. A similar groundwater high in northern Warren County has a similar pattern. North of it, groundwater moves to the southeast to the Missouri River in St. Charles County while south of it, water moves to the southwest.

PENNSYLVANIAN AQUIFER

The Pennsylvanian strata in the Northeastern Missouri groundwater province are generally of low permeability and are not considered to be an important water-supply source. Thus, no groundwater storage estimates were made for these materials. The Pennsylvanian is absent throughout much of the eastern part of the province. In the southern part of the province, the Pennsylvanian is from zero to about 100 ft thick, and is not considered a significant aquifer. Its thickness increases to the north and northwest where it can be as much as 300 ft thick. Yields of wells penetrating the Pennsylvanian are generally very low, ranging from nearly zero to perhaps as much as 10 gpm, but averaging less than 3 gpm. Like in northwestern Missouri, the quality of water from the Pennsylvanian is, at best,

marginal. It generally contains excessive sulfate, iron and total dissolved solids.

There are opportunities for bedrock supplies from the Moberly Sandstone in central Randolph County and the adjacent part of western Monroe County. This channel sandstone underlies an area of about 87 mi². It is locally as much as 150 ft thick, and potentially can yield as much as 50 gpm (Gann and others, 1971). However, the average yield of wells penetrating the Moberly Sandstone is generally less than 15 gpm. Assuming an average saturated thickness of 50 ft, and a specific yield of 0.01, the Moberly Sandstone is estimated to contain about 9.1 billion gallons, or about 28,000 acre-ft water. Since yields and water quality are typically poor in other Pennsylvanian bedrock units in the province, no groundwater storage estimates were made for them.

GLACIAL DRIFT AQUIFER

In much of northeastern Missouri north of the freshwater-salinewater transition zone, the glacial drift is the only aquifer that is available. This is particularly true west of the area where Mississippian strata subcrop directly beneath the glacial drift. The glacial drift in the northeast Missouri locally contains fairly thick sequences of medium- to coarse-grained sand and fine to medium gravel. However, these seemingly permeable deposits yield only small to moderate amounts of water to wells, and the recharge or recovery of water in the wells is slow. This may indicate that the permeable sand and gravel bodies are hydrologically isolated, and are surrounded by low-permeability silt and clay in the drift. Available information indicates that the hydrologic characteristics of the drift in this province are much different from those of the glacial deposits in northwestern Missouri.

Relatively large-diameter dug or augered wells are generally used in this area because of the low permeability of the glacial drift. The wells allow a large volume of water to accumulate in them even through the yield of the aquifer may be only a gallon per minute or less. There are a few very local exceptions,

and these are quite probably the result of wells drilled into unmapped preglacial valley deposits.

The cities of Brasher in Adair County and Palmyra in Marion County are among the very few towns in northeast Missouri that have wells completed in glacial drift. Wells at Brasher are low-yield, and can produce about 35 gpm. Palmyra's wells are in a pre-glacial channel, and produce from coarse sand and gravel. The wells are about 100 ft deep, and can reportedly produce more than 600 gpm.

Groundwater movement in the glacial deposits is generally toward the local modern drainage. Water recharged to the drift in upland areas moves down-gradient towards nearby streams. The rate of groundwater movement is very low due to low-permeability drift. The best evidence for the low rate of groundwater movement through the glacial materials is the flow characteristics of area streams. Major rivers in northeast Missouri that drain several hundred square mile watersheds have very low dry-weather flows. Many of these streams even cease flowing during prolonged dry weather due to the low rate of groundwater inflow into the streams.

Groundwater storage estimates for the glacial drift aquifer in northeast Missouri are based on much less information than those made for northwest Missouri. All or parts of 10 counties, Adair, Clark, Knox, Lewis, Macon, Monroe, Randolph, Schuyler, Scotland and Shelby, contain glacial deposits that are greater than 100 ft thick. It is assumed that 10 percent of the vertical extent of glacial deposits thicker than 100 ft contains clean, water-saturated sand, and that the specific yield of the glacial drift is 0.05. Based on these assumptions, the glacial drift in northeast Missouri contains about 392 billion gallons, or about 1.2 million acre-ft.

Total dissolved solids in groundwater from glacial drift ranges from approximately 340 mg/L to almost 3,000 mg/L (Gann and others, 1971). In areas where the dissolved solids are higher, calcium sulfate seems to be the predominant water type. This may indi-

cate leakage of water from the underlying bedrock formations. Sulfate ranges from about 15 mg/L to nearly 1,500 mg/L. Chloride in groundwater derived from glacial drift ranges from less than 10 mg/L to as much as 300 mg/L. In those instances where chloride is high, sodium is also high, indicating a bedrock source for at least part of the water. Water produced from glacial drift generally contains excessive manganese and iron. Manganese concentrations range from zero to more than 2.0 mg/L, with the average concentration being approximately 0.10 mg/L. Although a few samples contain no manganese, almost all water samples from glacial drift in this province have more than 1.0 mg/L of iron, and many have concentrations that range between 9.0 and 20 mg/L. Water with dissolved iron in concentrations above 0.3 mg/L and manganese above 0.05 mg/L will stain laundry, leave iron stains on plumbing fixtures, and generally have a metallic taste.

The water table in the glacial drift is generally very shallow, typically only a few feet below ground surface. Water levels in glacial drift wells fluctuate in response to precipitation. Unlike in the Ozarks where shallow bedrock wells typically show rapid, pronounced response to precipitation, glacial drift wells respond more slowly. Figure 66 is a groundwater-level hydrograph from a hand-dug glacial drift well in Schuyler County. This well is about 30 ft deep, and there are no other producing wells within one-half mile. Water-level rises in this well are due to recharge from local precipitation. Water-level declines are due to water draining from the aquifer into nearby surface drainages, and to a lesser extent transpiration. Despite its shallow depth, water-level changes in this well very slowly due to the low permeability of the glacial drift in this area. The lack of appreciable water-level change in 1988 and 1989 is due to low precipitation during those years. Precipitation measured at Kirksville, about 30 miles south of the observation well and the closest long-term National Weather Service observation station, was only about 15.91 inches in 1988 and 30.42

inches in 1989. Precipitation during 1990, 1991 and 1992 was more normal, ranging from 34.57 to about 44.4 inches. The very high water-levels observed in 1993 and 1995 were due to very wet conditions. For example, precipitation measured at Kirksville in 1993 exceeded 51 inches.

ALLUVIAL AQUIFERS

The most significant alluvial aquifers in the Northeastern Missouri groundwater province are, of course, the alluvial deposits of the Missouri and Mississippi rivers. Both of these aquifers have been discussed previously in this report, and will not be discussed further here. The alluvial deposits of the major Missouri and Mississippi river tributaries in the province are relatively untested. Some of the alluvial deposits of these smaller rivers may be capable of yielding 5 to 25 gpm for domestic supplies in upstream reaches where sufficient permeable sand and gravel are present. Where the deposits are thicker than 50 feet, the alluvial materials may yield as much as 100 gpm (Gann and others, 1971). The alluvium

along the downstream reaches of the Fabius and Salt rivers probably has the best water possibilities of the northeastern Missouri rivers. However, drilling studies would be needed to substantiate this.

Sparse data are available concerning the quality of groundwater contained in alluvial valleys in the the Northeastern Missouri groundwater province. It is probably safe to assume that the alluvial waters of the Mississippi River tributary streams would be similar in chemical quality to that in the alluvium of the Mississippi River. Iron and manganese concentrations are probably above the recommended limits for most supplies, and would require some sort of iron removal treatment prior to use.

GROUNDWATER CONTAMINATION POTENTIAL

Groundwater contamination potential varies widely in this province because of the many different types of aquifers and the different geologic settings. Shallow Mississippian-age and older bedrock in the extreme eastern and southern parts of the province, where not

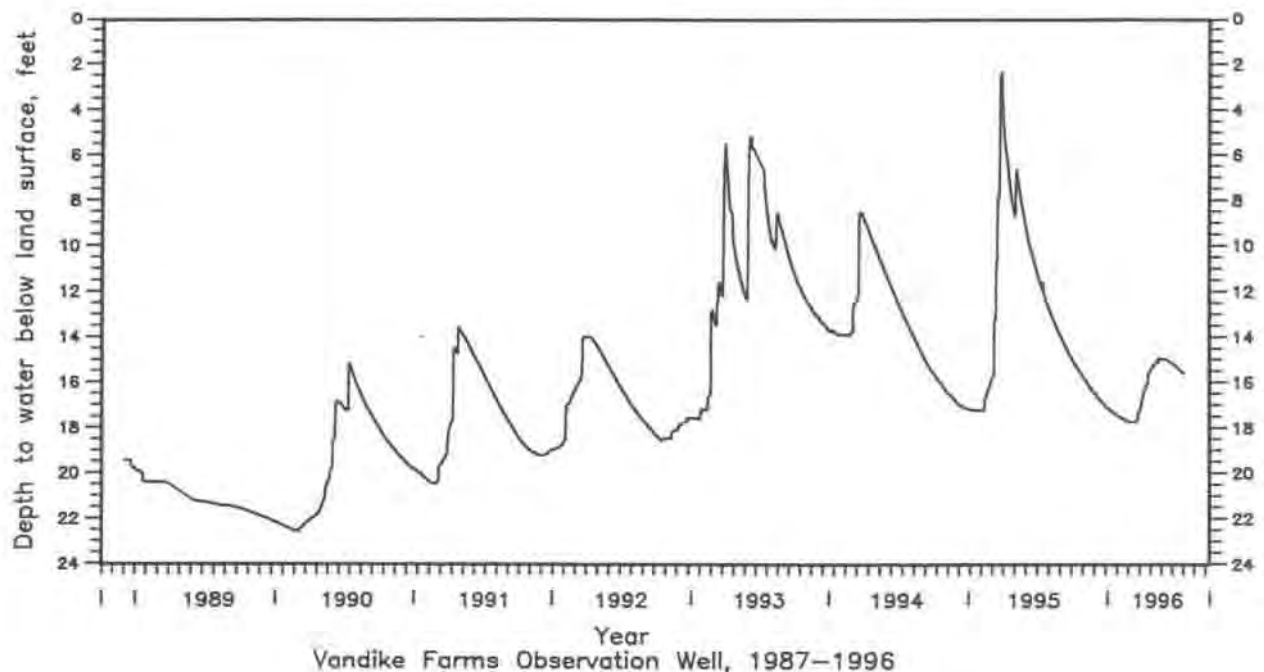


Figure 66. Groundwater-level hydrograph, Vandike Farms observation well, Schuyler County.

covered with low-permeability glacial drift, have much the same contamination potential as the same rock units in the Springfield and Salem plateaus. Where at least a few feet of glacial drift or Pennsylvanian-age bedrock overlies them, the potential for contamination due to surface activities is greatly diminished. Since most of the area south of the freshwater-salinewater transition zone is covered with Pennsylvanian strata, glacial drift, or both, bedrock aquifers here are not particularly prone to contamination.

Between Palmyra and St. Charles there are several areas where karst development occurs in Mississippian-age and older carbonate bedrock. Sinkholes, losing streams, caves and springs can be found in this area paralleling the Mississippi River, but the karst here is typically not nearly as well developed as it is in parts of the Salem and Springfield plateaus. Improper waste disposal in these small karst areas can adversely affect shallow groundwater quality, particularly at the numerous small springs draining the karst systems.

There is another, much more extensive karst area in the very southwest corner of this province in southwest Boone County. The Burlington-Keokuk Limestone here hosts numerous caves, the largest of which is the Devils Icebox south of Columbia. The Devils Icebox drains a very extensive sinkhole plain and losing streams that overlie or are adjacent to it. Improperly sited and poorly constructed private waste-disposal systems, barnyard runoff, and trash dumped in sinkholes caused pollution problems in this cave for many years, but more stringent zoning standards, coupled with education and development of

central sewer systems, have greatly decreased the introduction of wastes into this karst system.

The glacial drift deposits in the Northeastern Missouri groundwater province are generally finer-grained and of lower permeability than those in the northwestern part of the state. Deeper horizons in the drift are not typically affected by surface activities, but shallow groundwater in the upper few feet of the drift is commonly affected by septic systems and agricultural activities. Bacterial quality and nitrate levels for all supplies derived from very shallow unconsolidated sediments may be suspect. Since they contain no casing, per se, hand-dug wells in glacial drift and alluvium are especially prone to contamination. Augered wells, since they contain some type of casing, can be sealed, but their shallow depths more easily allow the introduction of surface water and shallow vadose water that may contain bacteria. While persons using private groundwater supplies in all of Missouri's groundwater provinces should test their water on a regular basis, it is most important to do so in northern Missouri. Northern Missouri, especially northeast Missouri, has historically had the greatest incidence of serious health problems resulting from poor-quality private water supplies, typically due to bacteria or high nitrate concentrations in shallow glacial drift wells. Contamination of water, resulting from a combination of poor waste disposal and fertilizing practices and poor well construction, is still a major concern in areas where shallow hand-dug and augered wells are still widely used by rural residents.

WEST-CENTRAL MISSOURI GROUNDWATER PROVINCE

INTRODUCTION

The West-Central Missouri groundwater province is bounded on the south and east by the Springfield Plateau groundwater province, by the Missouri River to the north, and the Kansas-Missouri boundary line to the west. It includes all or parts of 12 counties including Jackson, Cass, Bates, Vernon, Barton, St. Clair, Henry, Johnson, Lafayette, Pettis, Saline and Cooper, and encompasses an area of about 5,080 mi². Most of this area is within the Osage Plains physiographic region. The eastern and southern margins of the province coincide with the freshwater-salinewater transition zone. Thus, the deeper aquifer zones of the Springfield Plateau, Ozark, and St. Francois aquifers throughout the West-Central Missouri groundwater province contain water that is too highly mineralized for most uses. With perhaps the exception of the igneous rock area of the St. Francois Mountains, the Osage Plains of west-central Missouri probably have the least potable groundwater resources in the state. This has prompted the widespread development of rural water districts to serve much of the western part of this area. Most of the public water supplies in the Osage Plains depend on surface water for their raw water supply source.

GEOLOGY

Pennsylvanian-age formations form the bedrock surface throughout much of this province. The only exception to this is in southern and eastern parts of Saline County, and extreme northwestern Cooper County, where Mississippian-age bedrock is the shallowest consolidated rock (figure 67). The older Mississippian, Ordovician and Cambrian formations that crop out in the Ozark plateau are also present in the subsurface in west-central Missouri. However, since these older formations contain highly mineralized water in this province and are not usable aquifers, they will not be discussed further. Thin deposits of glacial drift overlie the bedrock formations in a narrow band just south of the Missouri River in Jackson, Lafayette, Saline, and Cooper counties. Table 17 is a stratigraphic section showing formations which underlie this province.

Mississippian-age rocks which directly underlie Quaternary sediments in Saline and Cooper counties are Osagean Series, and the shallowest bedrock unit is the Burlington-Keokuk limestone. The Burlington-Keokuk, as in the Springfield Plateau groundwater province, is a coarsely-crystalline limestone, with scattered layers of chert nodules.

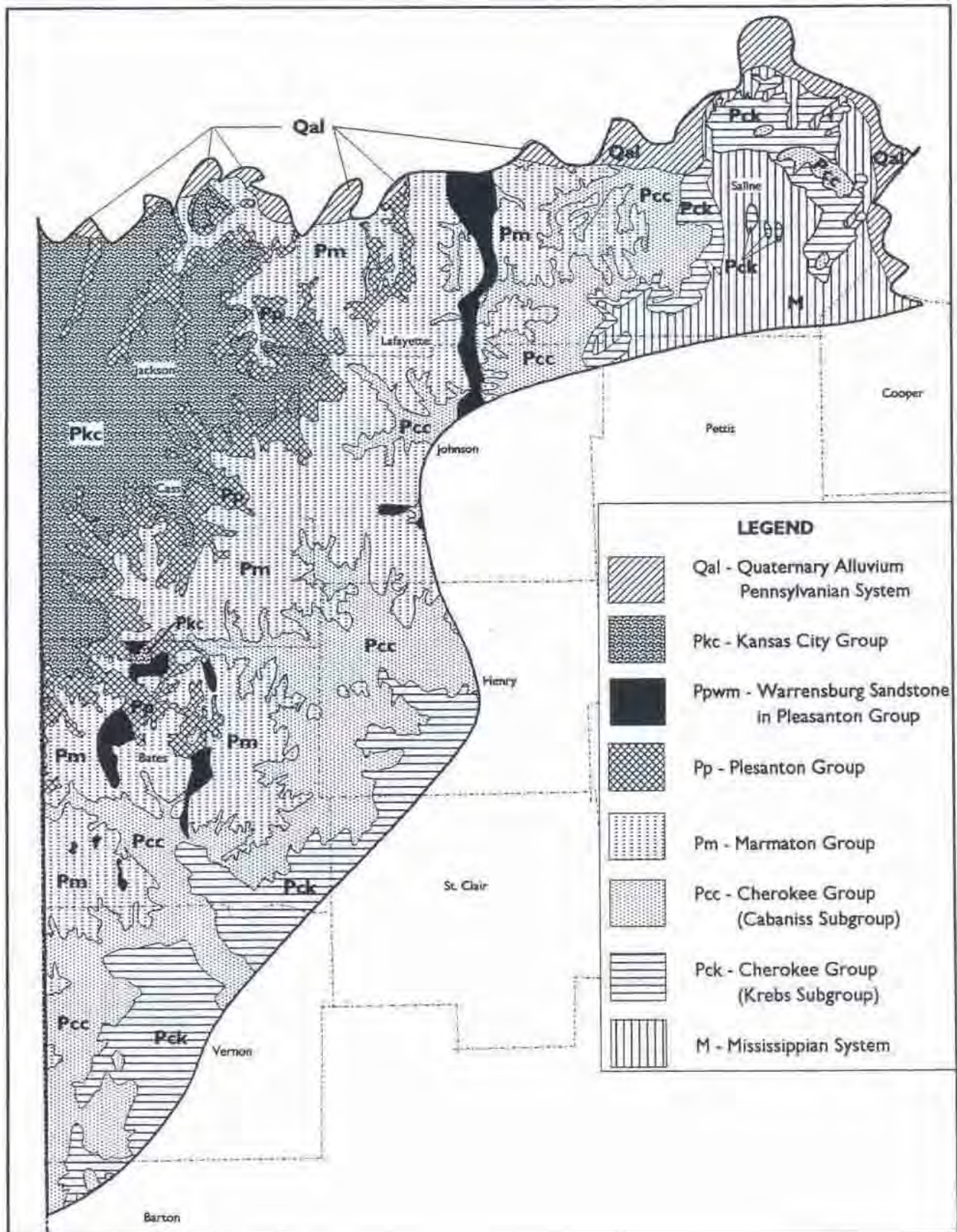


Figure 67. Generalized geologic map of the West-Central Missouri groundwater province. Geology from the *Geologic Map of Missouri* (DGLS, 1979).

System	Series	Group or Formation	Lithology	Hydrology
Quaternary	Pleistocene and Recent	Undifferentiated glacial drift and alluvium	Clay, silt, sand and gravel, in northern part of province, just south of the Missouri River is glacially derived. Some loess near the river valley.	Missouri River alluvium yields >1,000 gpm. Drift and alluvium-filled preglacial channels may yield 50 to more than 500 gpm. Elsewhere, drift may yield 0-5 gpm.
Pennsylvanian	Missourian	Kansas City	Massive limestone formations with intervening shale formations. Some of the shale intervals have included sandstone beds. In the lower part of the group these are thin black, fissil shale members.	Small amounts of water (1-3 gpm) available from limestones and black shales near the outcrop line. Where more deeply buried, water is highly mineralized.
		Pleasanton Group	Thick clastic shale with a basal siltstone or very fine-grained sandstone. Locally, there are two other thick channel sandstones in the upper half of the group.	Not considered to be water bearing. Locally, may yield very small amounts of water from sandstone beds. Water may be poor in quality.
	Desmoinesian	Marmaton Group	Fewer sandstone bodies than preceding group, with more thin limestones and thick shale sequences.	
		Cherokee Group and Krebs Subgroup	Thin sandstones and siltstones with intervening shales. The shales locally have coal seams. Thin limestone beds occur at widely scattered intervals.	May yield small amounts of water from sandstones, (3-20 gpm). Water may be poor in quality
Mississippian	Osagean	Burlington Limestone	Medium- to coarse-crystalline, medium- to thick-bedded limestone.	Yields very small amounts of water to wells locally. May contain highly-mineralized water.

Table 17. Stratigraphic section of the West-Central Missouri groundwater province.

Because of the cyclic nature of the Pennsylvanian deposits, which overlie the Mississippian strata, there are repetitive occurrences of lithologic types. The sheer number of individual thin formations in the Pennsylvanian necessitate that it be discussed by groups rather than by individual formations.

The Cherokee Group in this province is composed of thin sandstone and siltstones, with intervening shale bodies. The shales locally contain thin coal seams. Thin marine limestone beds are present throughout the section at scattered intervals. The most persistent lithologies of the Cherokee are the thick shale and the sandstone sequences.

Overlying the Cherokee Group in this province is the Marmaton Group. The Marmaton differs from the underlying Cherokee by having fewer sandstone bodies within the formations, and more thin limestone formations with intervening thick shale sequences. The most persistent lithologies of the Marmaton are the thick shales with thin limestone beds.

Overlying the Marmaton Group, is the Pleasanton Group. The base of the Pleasanton marks a break in the depositional sequence during Pennsylvanian time, forming a regional disconformity (Howe, 1961). The Pleasanton lithology in the West-Central groundwater province is predominantly a thick sequence of shale with a basal siltstone or very fine-grained sandstone. Two other thick sandstone bodies are present locally in the upper half of the group. These sandstones combined are called the Warrensburg Sandstone, and are channel sandstones that are very similar to the Moberly Sandstone described previously in the Northeastern Missouri groundwater province.

Overlying the Pleasanton Group is the Kansas City Group. The Kansas City Group is typified by massive limestones with intervening shale formations. Topographically, it forms an escarpment at its outcrop, and is in stark contrast to the underlying thick shale sequences of the Cherokee, Marmaton and Pleasanton groups. Thin, fissile, black shales

are present in some of the limestone formations in the lower part of the Kansas City Group. Locally, a few of the shale units have beds of fine-grained sandstone. The most persistent lithology apparent in the Kansas City Group is limestone.

The southern extent of Pleistocene glaciation, shown previously in the report in figure 58, roughly parallels the Missouri River, and passes through the northern tier of counties in this province. Quaternary-age clastic sediments consisting of clay, silt, sand and gravel are present as far south as southern Saline and central Cooper counties. These sediments are relatively thin over much of the area. This is likely because near the southern extent of the glaciers advance, the thickness of the ice was probably less than to the north, and the amount of debris transported was also proportionally less. There is a buried alluvial valley in Saline County that trends northwest-southeast across the county. It is either a preglacial channel, or a product of ice-damming of the Missouri River during glaciation. Wells drilled into this buried valley show thicknesses of glacial drift of 50 to 125 ft.

HYDROGEOLOGY

The groundwater resources of this province are meager. Table 17 shows the groundwater characteristics of the various rock groups. Pennsylvanian-age bedrock units are locally capable of yielding modest quantities of marginal quality groundwater. The greatest groundwater potential is alluvial and drift-filled preglacial valley deposits along the northern edge of the province.

PENNSYLVANIAN BEDROCK AQUIFER

Small quantities of groundwater, generally one to three gallons per minute, are available to wells drilled into sandstone units in the Cherokee Group, particularly near the crop line of the group, in Saline, Lafayette, Johnson, Henry, Bates and Vernon counties. Wells drilled to depths no greater than 200 ft can usually obtain small quantities of marginal

quality water in these areas. Further to the west, away from the outcrop line of the group, the units are more deeply buried, and water quality is poorer. This is due to the extremely low vertical and horizontal permeabilities of the units, and the low groundwater gradients within the formations. With low vertical permeabilities, recharge potential is also quite low. Permeabilities in the Marmaton Group are even lower than those in the underlying Cherokee Group. Very few wells drilled into this sequence of rocks yield adequate amounts of potable water to sustain even the most modest domestic needs. For this reason, many farm families in areas underlain by the Marmaton Group must use cisterns or some sort of surface water source for their water supply. What domestic wells are able to obtain water from the Marmaton Group, do so from the scattered sandstone bodies.

The Pleasanton Group exhibits even lower permeabilities and potential for groundwater supply than the underlying Marmaton Group. What small amounts of water that can be locally recovered are from the sandstone found at the base of the group, and from the north-south trending, sandstone-filled channel, which trends from northern Henry County to the Missouri River in Lafayette County, passing through Warrensburg. This, the Warrensburg Sandstone, underlies an area of about 106 mi². About 56 mi² of the area that it underlies is within the West-Central Missouri groundwater province, the remaining 50 mi² is south and east of the freshwater-salinewater transition zone in the Springfield Plateau groundwater province. In northern Johnson and Lafayette counties, well logs show the Warrensburg to be from about 100 ft to a maximum of 150 ft thick. Yields of 10 to 15 gpm are locally possible from the two sandstones comprising this unit; occasionally yields of as high as 25 to 30 gpm are reported. Yields of wells penetrating the lower sandstone usually range between one to three gallons per minute. Assuming a saturated thickness of 100 ft and a specific yield of 0.05, the Warrensburg

Sandstone contains about 58.4 billion gallons of recoverable water, or about 179,000 acre-ft.

The Kansas City Group has slightly better potential than the Pleasanton and Marmaton groups for yielding water to wells. The thicker limestone units may yield water from bedding planes and fractured intervals, and the black, fissile shales found in the lower part of the Group have fair horizontal permeabilities. Wells drilled near the outcrop line of the group, where the units are not deeply buried, are able to obtain three to five gpm from the limestones and black shales. As in the area underlain by Cherokee Group sandstones, wells drilled deeper than approximately 200 feet usually encounter mineralized water.

A somewhat unusual well recently drilled in Jackson County shows that under certain circumstances the Kansas City Group can yield relatively large quantities of water. This well, or more accurately a slightly inclined bore hole, was constructed to house a fiber optics cable. The 8-inch diameter hole was drilled through a ridge top overlooking the Missouri River just downstream of where the Kansas River enters the Missouri River. The southern end of the borehole is some 75 ft higher than the northern end, which exited the hillside near the edge of the Missouri River alluvium. Most of the hole is in limestone, probably the Winterset Member of the Dennis Formation or the uppermost Bethany Falls Member of the Swope Formation. Upon exiting the ground, water began discharging from the hole at an estimated rate of 300 gpm, and the flow rate did not appreciably decline for a three-month period. Specialized grouting techniques had to be employed to seal the casing in the drillhole. The quality of the water discharging from the hole strongly indicated it was from the Pennsylvanian strata. Chloride and sulfate contents were about 350 and 450 mg/L, respectively, and total dissolved solids was about 1,500 mg/L. The calcium-magnesium ratio indicated that the water had been in contact with limestone. Apparently, the slightly inclined drillhole intersected bedding plane and

joint openings that were sufficiently interconnected to allow a large quantity of water to drain from this normally low-yield unit (Dave Taylor, 1997; personal communication).

Direction of groundwater movement in the shallow Pennsylvanian bedrock is topographically controlled. Potentiometric surface gradients are very low in the deeper Pennsylvanian strata. Direction of movement in the more deeply buried rocks is toward the north.

Groundwater quality in this province, even from shallow wells, is at best marginal. Total dissolved solids content of water from relatively shallow wells producing from Pennsylvanian strata range between 450 mg/L and 1,500 mg/L, with the average being approximately 750 mg/L. The constituents that typically cause the elevated concentrations are sodium and chloride. Chloride concentrations are frequently in excess of 250 mg/L. The reasons for higher mineral concentrations are low recharge rates for water entering the system, low vertical and horizontal permeabilities, which cause poor groundwater circulation, and long-term residence of groundwater in the system. The dissolved solids concentration of water generally increases as the length of time it is in contact with the earth materials increases.

It is difficult to estimate the volume of potable groundwater in the Pennsylvanian aquifer in this area. For calculation purposes, it is assumed that there is 50 ft of saturated material containing marginally usable groundwater, and that the specific yield is 0.01. Based on this, the Pennsylvanian aquifer in west-central Missouri, which covers an area of about 4,500 mi² is estimated to contain about 454 billion gallons, or about 1.4 million acre-ft.

ALLUVIAL AND GLACIAL DRIFT AQUIFERS

The most significant alluvial aquifer in this area is the Missouri River alluvium, which was discussed in detail earlier in the report. There are two other unconsolidated alluvial or glacial drift aquifers that have the capability of

supplying relatively large quantities of good quality water. The first is a 16-mile-long, 1- to 2-mile wide alluvium-filled channel that begins at the southern edge of the Missouri River floodplain in central Jackson County, extends to the southeast to Lake City, then trends to the northeast and intersects again with the Missouri River alluvium in northeastern Jackson County (figure 68). This channel likely formed as the result of ice damming of the ancestral Missouri River during the Ice Age, forcing the river to the south where it eroded a new bedrock channel. The new channel included part of the lowermost Little Blue River channel, which at that time flowed to the east-northeast. Later, after the ice sheets had retreated, the river resumed its former coarse and abandoned the alluvium-filled bedrock channel. Today, the Little Blue River follows this valley from Lake City, northwest, to the Missouri River, and Fire Prairie Creek follows it from Lake City to the northeast and east through Buckner to where it reconnects with the Missouri River valley.

Much of the knowledge concerning this buried channel comes from studies performed in the early 1940s when the Lake City Ordnance Plant (Remington Arms Co.) was built in the valley overlying the buried channel. Several water supply wells were constructed in the buried channel. Most encountered 80 to 90 ft of alluvial materials, the lower part of which was coarse sand and gravel. Water levels were initially about 15 to 20 ft below land surface, and yields of wells constructed in the channel were generally 300 to 400 gpm (Anderson and Greene, 1948). Pumping tests showed that specific capacities were relatively high, ranging from 50 to about 200 gpm/ft of drawdown. The more favorable parts of the aquifer have transmissivities of from about 12,000 gpd/ft to 16,000 gpd/ft (1,604 to 2139 ft²/day). The alluvium in other parts of the buried channel may have significantly lower transmissivities. Groundwater storage estimates assume an average buried valley width of 1 mi, a length of 15 mi, a saturated

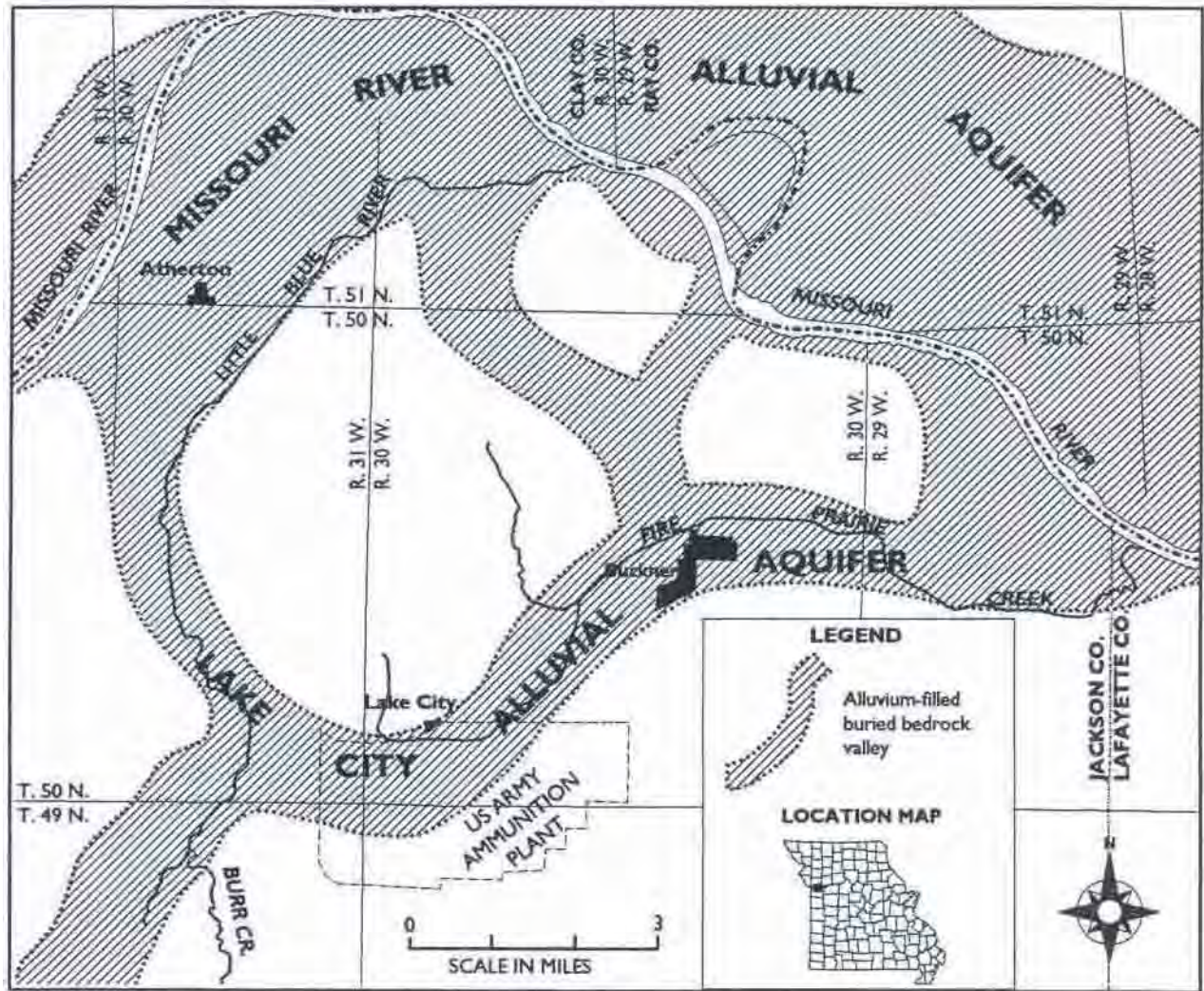


Figure 68. Lake City alluvial aquifer, Jackson County (buried valley locations from Anderson and Greene, 1948).

thickness of 60 ft, and a specific yield of 0.15. Based on this, the buried valley contains an estimated 28.2 billion gallons, or about 86,400 acre-ft of water. Part of the aquifer underlying the ordnance plant has been badly contaminated with organic chemicals due to improper waste disposal at the facility. Remedial investigations and aquifer clean-up projects are planned or underway.

The second clastic-filled channel trends to the southeast through Saline and the northwestern tip of Cooper counties. It, too, connects at both ends with the Missouri River alluvium. The western end of the channel begins at about Malta Bend, passes just north of Marshall and through Nelson where it crosses into Cooper County, and then trends nearly due east to where it intersects with the Missouri River valley. This channel likely developed during the Pleistocene due to glacial ice damming the Missouri River in the Big Bend area of the river somewhere near Glasgow. The damming of the river forced water to seek a new course to the south, and resulted in a bedrock channel that was later filled with sediments. It also caused glacial ponding, and associated sediment deposition at the upper end of the new channel.

Miller (1971) divides these glacial-fluvial deposits into three units (figure 69). The first, which is a large area of thick glacial drift west of Marshall and south of Grand Pass in northwest Saline and northeast Lafayette counties, has a moderate groundwater potential. In Saline County, this deposit underlies about 77 mi², and in Lafayette about 40 mi². The glacial drift ranges from locally absent to about 100 ft thick, is moderately fine-grained, and can yield 5 to 10 gpm.

Coarse sands and gravels up to about 150 ft thick accumulated beneath a high terrace known as Teteseau Flats. This deposit has been attributed to glacial ponding of the Missouri River (Bretz, 1965). The highest well yields are associated with the coarser part of this deposit, which covers an area of about 28 mi². The city of Marshall has 10 wells produc-

ing from it that can each supply about 1,000 gpm. Southeast of Teteseau Flats, the current surface channel, Salt Fork, roughly coincides with the buried channel. However, the channel narrows to less than 2 miles wide. In Saline County, the narrow part of the channel underlies an area of about 36 mi², and in adjacent Cooper County it underlies about 9 mi². Although the unconsolidated materials are as much as 100 ft thick, they yield more modest quantities of water than those underlying Teteseau Flats. In some places, properly located and constructed wells can yield, perhaps, 100 gpm, but numerous test wells and production wells drilled about a mile north of Marshall for a state school found yields to average closer to 50 gpm. Despite relatively thick, clean sand deposits in this channel, numerous well logs indicate that in many places it yields little or no water.

The total volume of groundwater contained in the glacial materials in Lafayette, Saline and Cooper counties is estimated to be about 214.5 billion gallons, or about 658,000 acre-ft. Of this, about 33.4 billion gallons or 102,400 acre-ft are in Lafayette County, and about 10.5 billion gallons or 32,340 acre-ft are in Cooper County. The remaining 170.6 billion gallons or 523,160 acre-ft are in Saline County.

The quality of water from these glacial and alluvial deposits is generally good. Total dissolved solids, chloride, and sulfate are generally within recommended drinking water parameters, but iron and manganese may be elevated. In some areas, highly-mineralized water ascending from deeper bedrock aquifers affects water quality in the lower parts of the glacial and alluvial aquifer.

GROUNDWATER CONTAMINATION POTENTIAL

The potential for groundwater contamination is low to moderate in the West-Central Missouri groundwater province. It is much lower than in any of the other provinces discussed in this report, due to low

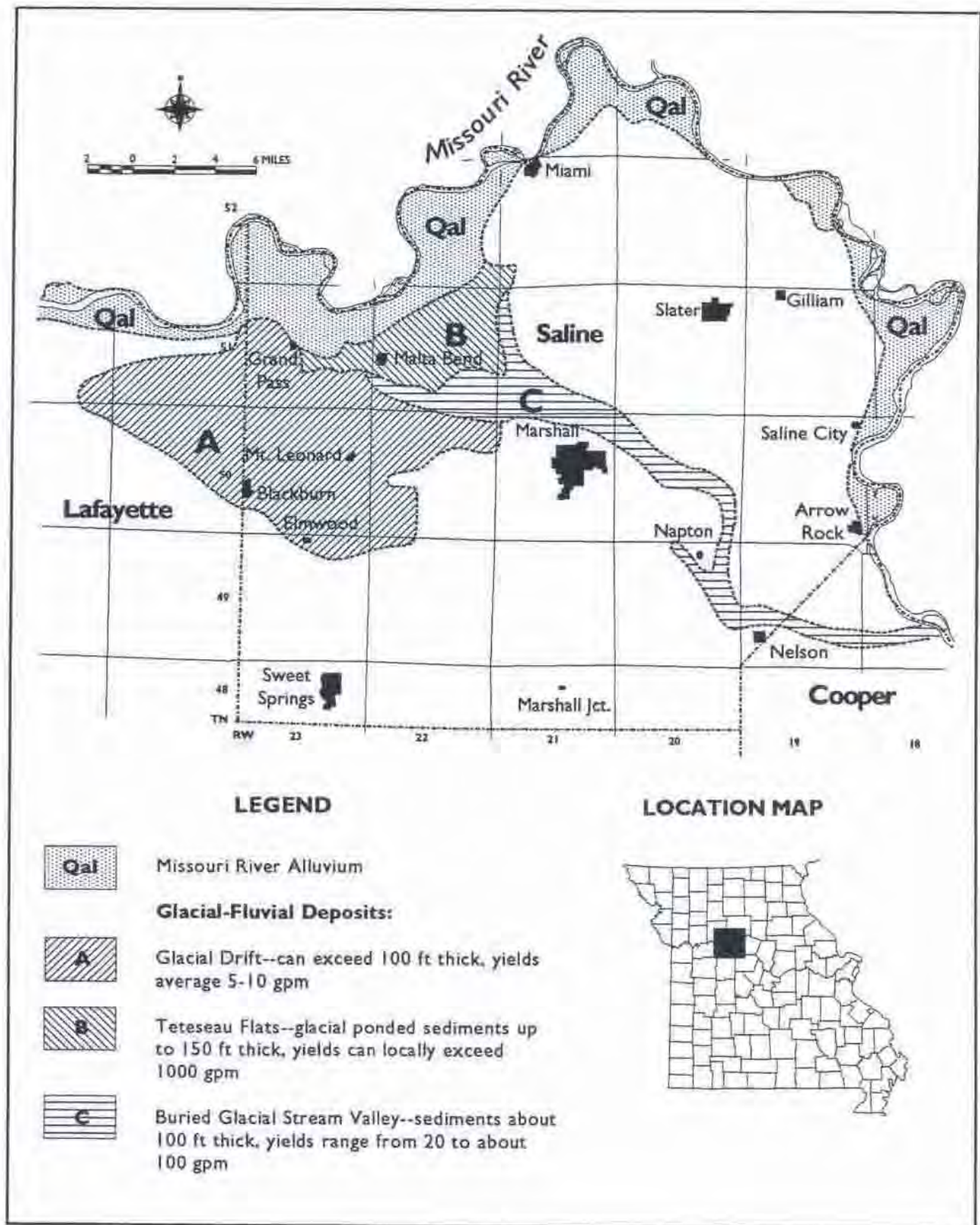


Figure 69. Preglacial valley and the Teteseau Flats area, Saline, Lafayette and Cooper counties (modified from Miller, 1971).

permeabilities of the underlying bedrock. Recharge is very limited, and circulation is very slow. Surface water is much more susceptible to contamination than the groundwater system.

Depending on the thickness and permeability of shallow alluvial materials, the alluvi-

al and glacial drift aquifers in the northern part of the province are more likely prone to contamination than the bedrock aquifers. Widespread groundwater contamination has occurred at the Lake City Ordnance Plant due, at least in part, to leakage from waste-disposal lagoons into the buried channel.

THE UTILIZATION OF GROUNDWATER FOR WATER SUPPLY IN MISSOURI

INTRODUCTION

The use of groundwater for water supply in Missouri is as much about drilling technology as it is about resource availability. Prior to the development and availability of drilling machines, groundwater use in the Ozarks mostly centered around springs. An afternoon's drive through the rural Ozarks will attest to this; many older homes and farmsteads were built near springs that not only supplied household and farm water needs, but also were used for cooling milk and other perishables. Larger springs often became the focal points for small communities, providing power to grist mills, saw mills, and other water-driven industries as well as water for the residents and their livestock. Towns large and small took advantage of springs; a few still do. Springfield's first public water supply was Fulbright Spring at the north edge of the city. Deep wells, surface-water reservoirs, and stream intakes were added as the city grew, but even today the spring still remains a very important source of raw water. Between 1971 and 1993, about 50 percent of the 110 billion gallons of water treated and distributed through the Fulbright Water Treatment Plant was supplied by Fulbright Spring. At the other end of the population scale, the village of Mill Spring in Wayne County, which has a population of about 252, until recently used a spring in town for public water supply. Most towns have found that the overall quality of untreated water from springs is generally much better than that of streams.

WATERWELL DRILLING IN MISSOURI

Before the turn of the century, the relatively few water wells in Missouri that were present were generally dug by hand, some to depths of more than 50 ft. It was not until after about 1900 that drilling machines were available for constructing large capacity wells for towns and cities, and many more years after that before even the most affluent private citizens could afford to have a well drilled. Prior to about 1930, groundwater was much more widely used in northern Missouri than in the Ozarks. It proved far easier to dig wells in the relatively soft glacial drift deposits in the northern half of the state where the water table was only a few feet below land surface, than in the residuum and bedrock of the Ozarks, where the water table was typically much deeper. Hand-digging a northern Missouri well had another advantage; if a usable quantity of groundwater was not encountered at a reasonable depth, the hole could still be used as a cistern for storing runoff water collected from roof-tops.

The first well drilled in the United States was not in search for water, but for a more valuable commodity...oil. The historic Drake oil well, drilled in 1859 near Titusville, Pennsylvania, reached a depth of 65 feet, and is credited for starting the American petroleum industry (Gatlin, 1960). The technology used to drill the Drake well, however, did not originate in the United States, but rather in China where the same drilling principals, although more crudely applied, had been used

for centuries to drill salt brine wells, some more than 3,000 ft deep (Driscoll, 1987). Water well drilling technology has to a great extent mimicked oil well drilling technology. Many of the techniques and much of the equipment developed for oil exploration and exploitation have been modified for use in the water well industry. However, both cable tool and rotary drilling equipment were first used for obtaining water, and later used in search of oil.

There are few industries other than the well drilling industry that rely so heavily on human ingenuity for success. The phrase "necessity is the mother of invention" could have easily been coined to describe water well drillers. Although the drilling rig does most of the physical work, the skill and experience of the driller is a key factor in the successful completion of a well. Essentially all of the drilling and construction of a well is carried out below ground where it cannot be directly observed. This normally presents few problems. But when difficulties arise, the experience of the driller is called upon to remedy the problem, whether it be fishing lost or broken equipment from the bottom of the drillhole, or salvaging a drillhole that encountered deeply-weathered or highly-fractured rock.

Throughout the years there have been many different types of drilling equipment used in Missouri. Some types of drilling rigs can be used for constructing all types of wells while others are very specialized and will only work when drilling through certain materials. The earliest drilled water wells in Missouri were constructed using a *cable tool drilling rig* (figure 70). The cable tool drill, also called a *churn drill* or *percussion drill*, uses a heavy, hardened steel bit attached to the end of a cable to drill the hole. The bit is repeatedly raised and allowed to fall about 20 to 40 times per minute. The impact of the drill on the bottom of the hole pulverizes the rock. Until groundwater is encountered, water is poured into the well to mix with the ground-up rock and other earth materials, called cuttings, to form a slurry. Additional drill cable is spooled out as the hole is deepened. After every five

feet of drilling, the cable and bit are pulled from the hole so that the cuttings can be removed from the well. A bailer, consisting of a long hollow tube with a dart valve at the bottom, is lowered to the bottom of the drillhole to remove the cuttings. The bailer is lowered using the sand line, which is a small diameter utility cable that is secondary to the heavier drilling cable. The dart valve is at the bottom of the bailer, and opens when the bailer strikes the bottom of the hole, allowing the cuttings to fill the bailer. When the bailer is lifted, the valve closes and the cuttings are transported to the surface.

Cable tool drilling rigs were the mainstay of the water well drilling industry for many years. Even today, numerous cable tool rigs are still used in Missouri, although faster rotary drilling rigs are used to drill the vast majority of the water wells. In fact, the older churn drills actually have a few advantages over their faster, newer counterparts. Cable tool rigs, because they are lighter, simpler, and less complicated, cost much less to purchase, and have much lower operating costs. A relatively small gasoline engine can power a cable tool rig where larger air rotary rigs require one or more large diesel engines. Since they can normally be mounted on relatively small truck frames, cable tool rigs can be more easily maneuvered into confined spaces. A major disadvantage of the cable tool rig is the drilling rate. A modern air-rotary drill can complete a well several hundred feet deep in a days time where as a cable tool rig may take a week or more to drill to the same depth. Despite this, in areas where there is deep weathering, large bedrock openings, and problems with the loss of drilling fluids, cable tool rigs are still preferred by many drillers.

The *rotary drilling rig* (figure 71) was introduced into the oil industry about 1901 when a rotary drilling rig was used to drill the discovery well at the Spindletop oil field near Beaumont, Texas. The rig, however, was brought from South Dakota where it had been used for drilling water wells in relatively soft sediments. The first rotary drilling bits were called fish-tail bits or drag-type bits. These

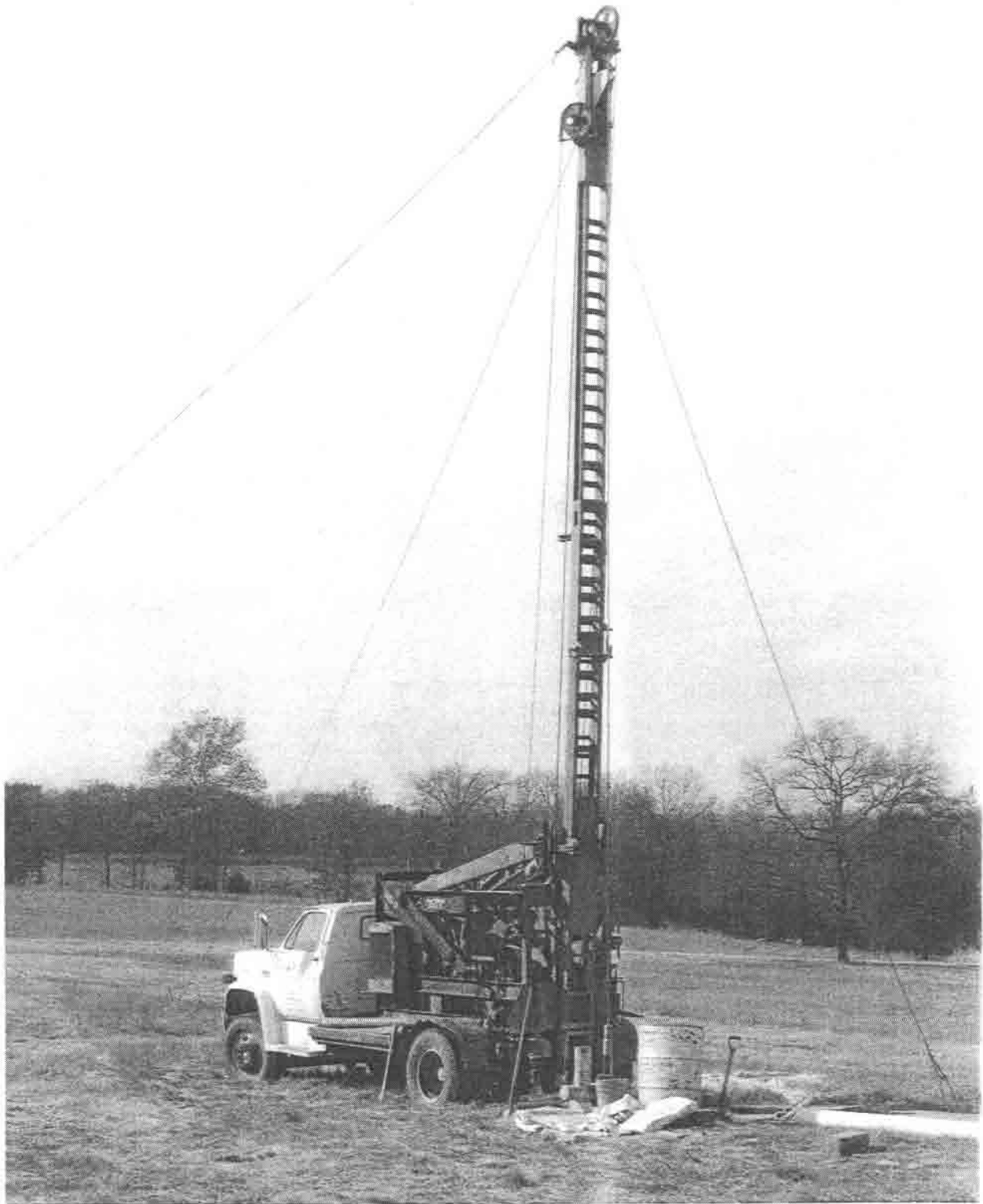


Figure 70. Cable tool drilling rig. Photo by Jim Vandike.

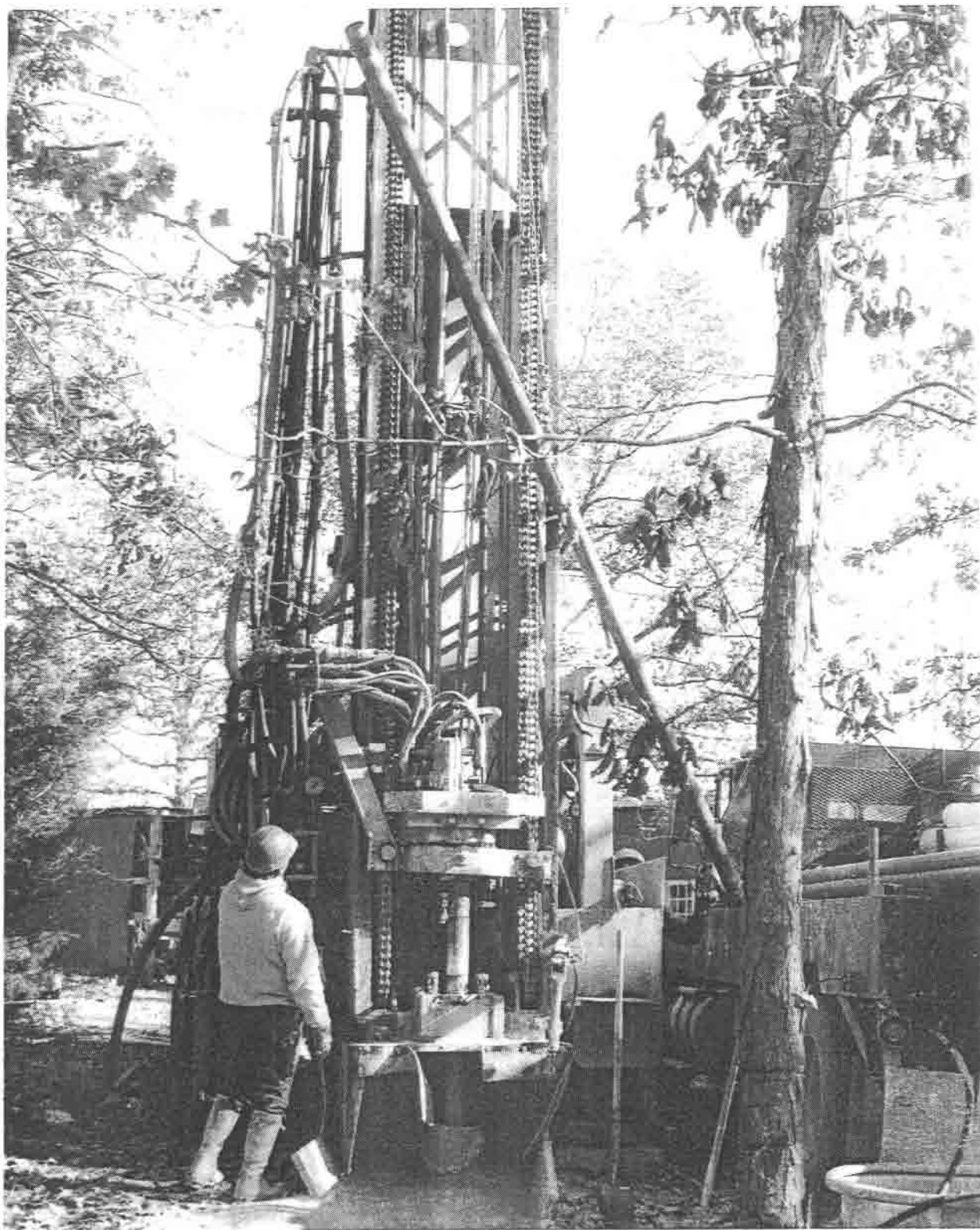


Figure 71. Rotary drilling rig. Photo by Jim Vandike.

were made of hardened steel, and could only be used for drilling in unconsolidated sediments or very soft rock such as shales. Roller or cone-type bits were later developed to allow drilling through harder rock units. Some of these use hardened-steel teeth, while others are equipped with tungsten carbide buttons. Within a few years after its introduction, rotary drilling began replacing the cable tool drill. Today, more than 90 percent of oil, gas, mineral test and water wells are drilled using rotary drilling equipment (Campbell and Lehr, 1973).

The rotary drilling method uses a bit placed at the end of a drill string consisting of hollow drill pipe and collars. The drill string is rotated from above and downward pressure applied. More drill pipe is added as the hole deepens. The drill pipe can be rotated one of two ways. The first rotary rigs used a stationary rotary table at the bottom of the drill rig to turn the drill pipe. The rotary table turns a square or fluted pipe called a kelly that is attached to the top end of the drill string. The kelly slides downward through the opening in the rotary table as the hole deepens. Cables and pulleys are used to raise the drill pipe. This method is still widely used in the oil industry or where very deep holes are drilled.

Most of the rotary water well drilling rigs in Missouri use a top-head drive. Here, the drill pipe is attached to a hydraulic motor that can move up and down the derrick. The hydraulic motor rotates the drill pipe, and the top-head is moved up and down using large hydraulic cylinders on the sides of the derrick. These can raise the heavy drill string, and also be used to transfer the weight of the drill rig to the drill string.

The cuttings are removed from the hole using one of several methods. The first rotary drilling rigs used water or other drilling fluid to clean the cuttings from the hole. The drilling fluid was pumped down the inside of the drill pipe. It exited through openings in the bit, and in the process cooled and lubricated the bit as well as removed the cuttings and broken rock. The drilling fluid moves up the hole to the surface where it is diverted into a

series of mud pits where the cuttings settle out. After the cuttings settle out, the drilling fluid is reused. In some instances, water is used as the drilling fluid. However, in the early days of rotary drilling it was found that other substances such as bentonite, barite, and other dense solids could be mixed with the water to improve removal of the cuttings, control loss of fluids into permeable formations, and stabilize the sides of the drillhole in formations prone to collapse.

Another rotary technique often used where wells are drilled into soft, unconsolidated sediments that are prone to collapsing into the drillhole is called *reverse circulation rotary drilling*. With this technique, drilling fluid, consisting mostly of water, is pumped down the borehole on the outside of the drill pipe, and is drawn back to the surface through the inside of the drill pipe. This technique is used predominately where very large diameter holes are being drilled in loose materials such as unconsolidated sands, or where the drillhole will not stay open using conventional rotary techniques. For example, wells in the Wilcox and McNairy aquifers in the Southeastern Lowlands are commonly drilled using the reverse rotary method. The velocity of the fluid filling the drillhole is low enough to preclude excessive erosion of the soft sediments. The drillhole must be kept full of fluid at all times, even when drilling ceases. Otherwise, the hole can collapse because of the loss of hydrostatic pressure on the walls of the bore hole.

Today, the most widely used rotary drilling technique in Missouri is *air rotary drilling*. With air rotary, large volumes of high-pressure air are forced down the drill stem to cool the bit and force the cuttings back to the surface. Normally, a small quantity of water and drilling additives are added to the air. The additives used are foams or soaps that help cool and lubricate the bit and aid in returning the cuttings to the surface. Probably the most significant development since the invention of the rotary drilling rig is the introduction of the pneumatic hammer bit. This type of bit operates much like a large diameter jack ham-

mer. It is powered by the high-pressure air that is forced down the drill pipe which causes the bit to rapidly strike the bottom of the drillhole while the drill stem is rotated. The use of a hammer bit increases the rate of drilling several fold over that of conventional roller-cone bits. Using a hammer bit, it is possible to drill several hundred feet per day through very hard rock.

Although rotary and cable tool drilling rigs can successfully be used to drill in most conditions, there are several other drilling machines that have been developed for drilling in special conditions. Several of these are used in Missouri. *Jet drilling* is used to construct relatively small diameter wells in unconsolidated sediments or very soft rock. With this technique, water is pumped down the drill stem under high pressure to exit at ports on the chisel-shaped bit. The drill rods and bit are raised and dropped much like the cable tool method, and the water forces the cuttings to the surface as well as helps break the soft formation around the bit. In Missouri, a variation of this method is commonly used to construct domestic wells in the Bootheel area. This method uses small diameter pipe, usually 2 inch, attached to a well screen with an open-bottomed point at its base. A retrievable tube passes through the well screen to the opening at the bottom of the screen. This prevents the water used to jet the well from exiting through the well screen. Rather, it exits through the hole at the bottom of the well screen and creates a void in the soft sediments. The cuttings are carried back to the surface. The pipe and well screen are pushed downward while water is pumped down the well. Wells can easily be constructed to depths greater than 20 ft in soft sediments using this method.

Another type of well often used in the Bootheel or where the sediments are soft and the water table is shallow is the driven well. A typical driven well in Missouri consists of a small diameter, usually 2 inch, well screen with a rugged point at its base. The well point and screen are driven into the ground; short sections of pipe are added as the well advances. In some conditions, the point can be

driven by hand with a sledge hammer. In other cases, a heavier slide hammer is used. Driven wells can be installed to depths of more than 30 ft, but are typically much shallower.

Auger rigs and bucket-auger rigs (figure 72) are commonly used to install large-diameter, relatively shallow wells in glacial drift or alluvium. The auger rig typically uses solid stem flight augers to drill in soft, stable materials such as clay-rich drift that is not prone to collapsing during drilling. This type of rig drills a large diameter hole that can be completed with concrete, tile, steel or plastic casing. In many respects, it is the modern day equivalent to the hand-dug glacial drift well that had a low inflow rate, but allowed a large quantity of water to collect in the bore hole.

The auger-bucket rig uses a cylindrical auger-bucket at the end of telescoping square drill pipe. This method, also called rotary bucket drilling, is used to drill large-diameter holes in unconsolidated sediments. Auger-type cutting blades excavate the earth materials and pull them upward into a cylindrical bucket. When the bucket is filled, a cable extracts the bucket and telescoping drill pipe. The bucket is raised above ground, swung to the side by the dumping arm, emptied, and then returned to the drillhole to excavate another load. The buckets are commonly 24 to 36 inches in diameter, and can easily drill 50 to 150 ft depths. When drilling in loose sand formations, water is pumped into the drillhole to maintain water pressure against the formation, much like reverse rotary.

Well drilling in Missouri is regulated by the Missouri Department of Natural Resources through its Division of Geology and Land Survey. Qualified drillers, pump installers, and contractors are issued permits, and only permitted drillers are allowed to construct wells.

TYPES OF WATER WELLS IN MISSOURI

The Missouri Department of Natural Resources divides water supply wells into two broad categories for regulatory purposes—



Figure 72. Bucket-auger drilling rig. Photo by Jim Vandike.

public water supply wells and private water supply wells. Determining which type of well is required for a particular purpose is based on several factors including the number of service connections, the number of people served, the length of time during a year the population is served, the proposed pumping rate, and how the water will be used.

Public water supply wells are divided into three categories—community public water supply wells, transient noncommunity public water supply wells, and nontransient noncommunity public water supply wells. Community public water supply wells are those with 15 or more service connections, or that regularly serve 25 or more people on a year-round basis. Community public water supply wells serve towns, cities, subdivisions, and mobile home parks. They generally serve the same population on a continuous basis, and must be designed by a Registered Professional Engineer.

Transient noncommunity public water supply wells are those with 15 or more service connections, or that regularly serve an average of at least 25 individuals at least 60 days out of the year. They are not designed to serve the same group of people on a regular basis. Transient noncommunity wells are used by such businesses as restaurants, motels, convenience stores and campgrounds. Nontransient noncommunity wells are those with 15 or more service connections, or that regularly serve an average of at least 25 individuals daily at least 60 days out of the year. They, however, can be used to serve the same people on a daily basis. Nontransient noncommunity wells are used to serve schools, factories and other large business. Neither nontransient or transient noncommunity wells are intended to supply a permanent population on a year-round basis. Most transient noncommunity well designs do not require the services of a Registered Professional Engineer. However, regulations require that noncommunity wells constructed for certain uses, such as schools, be designed by a Registered Professional Engineer. All Public Water Supply wells must be drilled by permitted well drillers. Public

water supply wells are administered by the Department of Natural Resources' Division of Environmental Quality-Public Drinking Water Program.

The water wells in Missouri that do not fit the criteria used for public water supply wells are considered private wells. Private water supply wells are administered by DNR's Division of Geology and Land Survey. To be considered a private water supply, the well must have fewer than 15 service connections and serve fewer than 25 people daily on a permanent basis. Two types of private wells are used to supply drinking water. The private domestic well can serve from one to three families, and must produce less than 70 gpm. Multiple family wells can serve from four to 14 service connections, but must serve a permanent population of less than 25 people. Generally, any well serving nine or more single-family dwellings, apartment units or condominium units, is assumed to be a public water supply well. Any well designed to produce more than 70 gpm is considered a high-yield well. High-yield private wells are typically used to supply industries or businesses where the water is not being consumed by the employees, or for agricultural irrigation.

WELL CONSTRUCTION IN MISSOURI

Well construction is also regulated by DNR. The Public Drinking Water Program must approve engineering plans and specifications for all community and nontransient noncommunity public water supply wells. They provide general guidelines for constructing transient noncommunity public water supply wells. The Division of Geology and Land Survey assists them by providing casing and total depth information for public water supply wells.

Private well construction standards, as well as those for monitoring wells and heat pump wells, are published by DNR's Division of Geology and Land Survey in Miscellaneous Publication No. 50, *Missouri Well Construction Rules*. It is beyond the scope of this report to discuss well construction in detail, but a brief overview of well construction

practices is needed to help show how groundwater in Missouri is obtained and protected. Rules and regulations governing the construction of wells in Missouri are periodically changed. People considering constructing new wells or modifying existing wells should contact DNR to obtain copies of current rules and regulations or guidance documents.

The construction standards used for public and private water wells in Missouri are intended to allow groundwater to be produced while protecting the aquifer and well from potential contaminants. Private water supply wells, which include private domestic wells, multiple family wells, and high yield wells, must be constructed in accordance with regulations developed by the Division of Geology and Land Survey. Regional minimum construction standards have been developed that allow drillers to construct most types of private wells in most areas of the state without having to obtain site-specific construction specifications. There are two exceptions to this: 1) the casing depths for high-yield private wells, which are typically used for irrigation and nonpotable industrial and commercial water supply, must be established by the Division of Geology and Land Survey; 2) private domestic wells drilled within a specific (currently 0.25 mi) distance from most of the large lakes in the state must be cased at least 50 ft below lake bottom. Lake-depth information is normally not readily available to well drillers, and casing depths for these wells are generally supplied on a case by case basis by the Division of Geology and Land Survey.

PUBLIC WATER SUPPLY WELLS DRILLED INTO BEDROCK

Public water supply wells drilled in areas where bedrock is competent, such as the Salem and Springfield plateaus and the freshwater area of northeast Missouri, typically consist of an unlined, open borehole below the casing. To construct these wells, the driller generally begins by drilling a relatively large-diameter hole through the soil and weathered bedrock until competent bedrock is reached. This hole is generally 8 inches in diameter

larger than the proposed finished well diameter. The driller installs surface casing into this hole. The surface casing is 4 inches in diameter larger than the permanent production casing, and its purpose is to prevent loose soil material and weathered rock from caving into the drillhole. After the surface casing is installed, the driller typically drills a pilot hole to below the proposed casing depth of the well. The cuttings are transported to the Division of Geology and Land Survey where they are examined by a geologist who determines if a suitable casing point has been reached. When an acceptable casing point has been reached, the driller reams the pilot hole to a diameter at least a nominal 4 inches greater than that of the casing. For example, if a finished well diameter of 12 inches is needed and surface casing is required, the surface casing will be 16 inches in diameter and will be set into a drillhole that is 20 inches in diameter. The 12 inch diameter casing will be set into a hole at least 16 inches in diameter.

Casing is installed into the drillhole and the open area between the wall of the drillhole and the outside of the casing. This is called the *annular space* and is completely filled with neat cement grout. Neat cement is a mixture of Portland cement and water. A maximum of about 6 gallons of water is used per 94 lb sack of cement. No sand or gravel is used, although small amounts of bentonite are sometimes mixed with the neat cement grout to counteract shrinkage or increase viscosity. The casing is generally steel weighing 19 lb/ft for 6-inch diameter, proportionally heavier for larger diameter casing. Community public water supply wells must be pressure grouted; the neat cement grout must be pumped down the inside of the casing, and forced back to the surface on the outside of the casing. Under some conditions, noncommunity public water supply wells can be grouted using a *tremie pipe*. With this technique, a small-diameter pipe is installed outside of the casing. Grout is pumped down the small-diameter pipe and forced back to the surface, filling the annular space. Sealing the casing full length with neat cement helps ensure that the well will not be

affected by surface water or shallow groundwater that is more likely to contain bacteria or other contaminants.

The length of casing needed for public water supply wells varies considerably with geologic conditions. In a few areas, as little as 150 ft of casing is used for transient noncommunity wells. Community public water supply wells generally have the highest construction standards. Casing lengths in these wells vary from about 300 ft to more than 900 ft, depending on the characteristics of the rock, water quality and other considerations. These wells are constructed to prevent surface water and shallow groundwater from impacting the well. Thus, most community public water supply bedrock wells require no water treatment, including chlorination.

After the grout is allowed to cure, generally a minimum of 72 hours, a drill bit slightly smaller in diameter than the casing is used to complete the hole to total depth. The total depth of the well depends on the volume of water desired and water quality. In general, there is little or no reason to drill deeper than where the necessary volume of water is obtained. However, in areas where high groundwater use increases the likelihood of groundwater-level declines, wells should be drilled somewhat deeper to allow for drawdown. Figure 73 shows typical construction of community public water supply wells in the St. Francois Mountains, Salem Plateau, and Springfield Plateau groundwater provinces.

PRIVATE WATER SUPPLY WELLS DRILLED INTO BEDROCK

The private domestic well can serve up to three families, but is generally designed to serve a single family or dwelling. The minimum length of casing required varies with the area. In the Ozarks, current standards require at least 80 ft of casing set a minimum of 30 ft into unweathered rock. Less casing may be required in the western, northwestern and northeastern parts of the state, while more casing is necessary near large lakes and in the Springfield area of Greene and northern Christian counties. There are a variety of approved

techniques that can be used to grout casing in private wells. Some of the techniques can be used only when the casing is less than a certain length, or in certain areas. Neat cement and bentonite are the materials used to seal the casing in most private wells.

Multiple family wells are intended to help fill the gap between private domestic wells and community public water supply wells. The multiple family well shares construction similarities with both the community and private wells. It can serve up to 14 service connections, but must not serve more than an average of 25 people on a permanent basis. Generally, any well serving more than eight families will likely exceed the 25 person limit, and is thus considered a public water supply. The length of casing required for a multiple family well is determined by region, and is the same as the minimum casing length for a private domestic well in the same region. The casing is lighter in weight (minimum 13 lb/ft for 6-inch diameter) than a public water supply well, but it must be set into a drill hole 4 inches in diameter greater than the casing and be grouted full length using pressure grouting or tremie pipe.

Bedrock irrigation wells are constructed similar to public water supply wells. The weight of casing used in them is greater than that for private wells, and they too require full length grouting. Also, the casing depths of irrigation wells are established on a case by case basis by the Division of Geology and Land Survey.

Figure 74 shows the construction of typical private bedrock wells in the Salem Plateau and Springfield Plateau groundwater provinces.

PUBLIC AND PRIVATE WATER SUPPLY WELLS DRILLED INTO UNCONSOLIDATED MATERIALS

Wells drilled into alluvium, glacial drift, and other unconsolidated deposits are constructed much differently than bedrock wells. In unconsolidated deposits, wells typically contain a well screen at the bottom of the casing that is set opposite of water-productive materials. Only a few feet of screen may be necessary for a private, low-yield well. High-

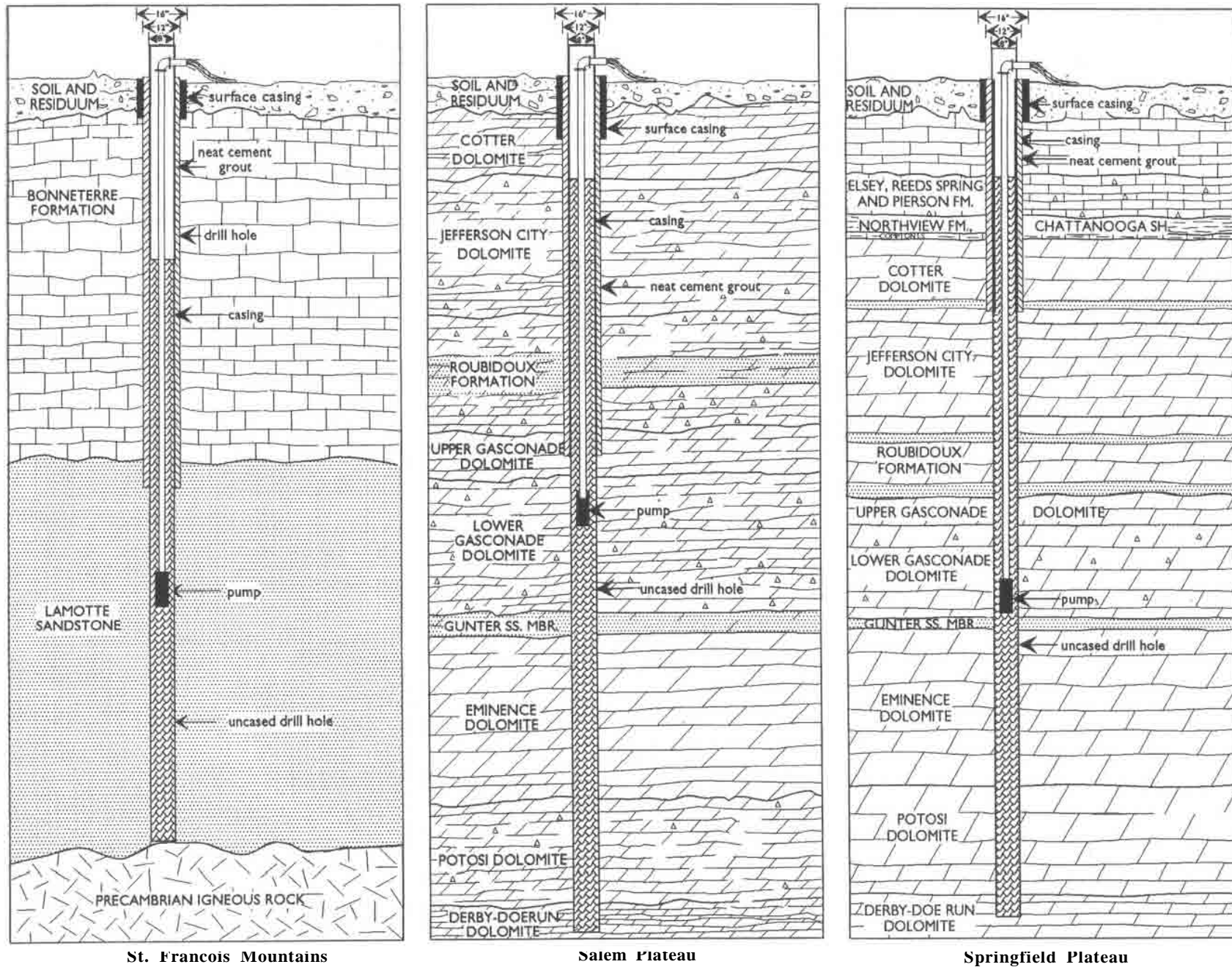


Figure 73. Typical public water-supply well construction in the St. Francois Mountains, Salem Plateau and Springfield Plateau groundwater provinces.

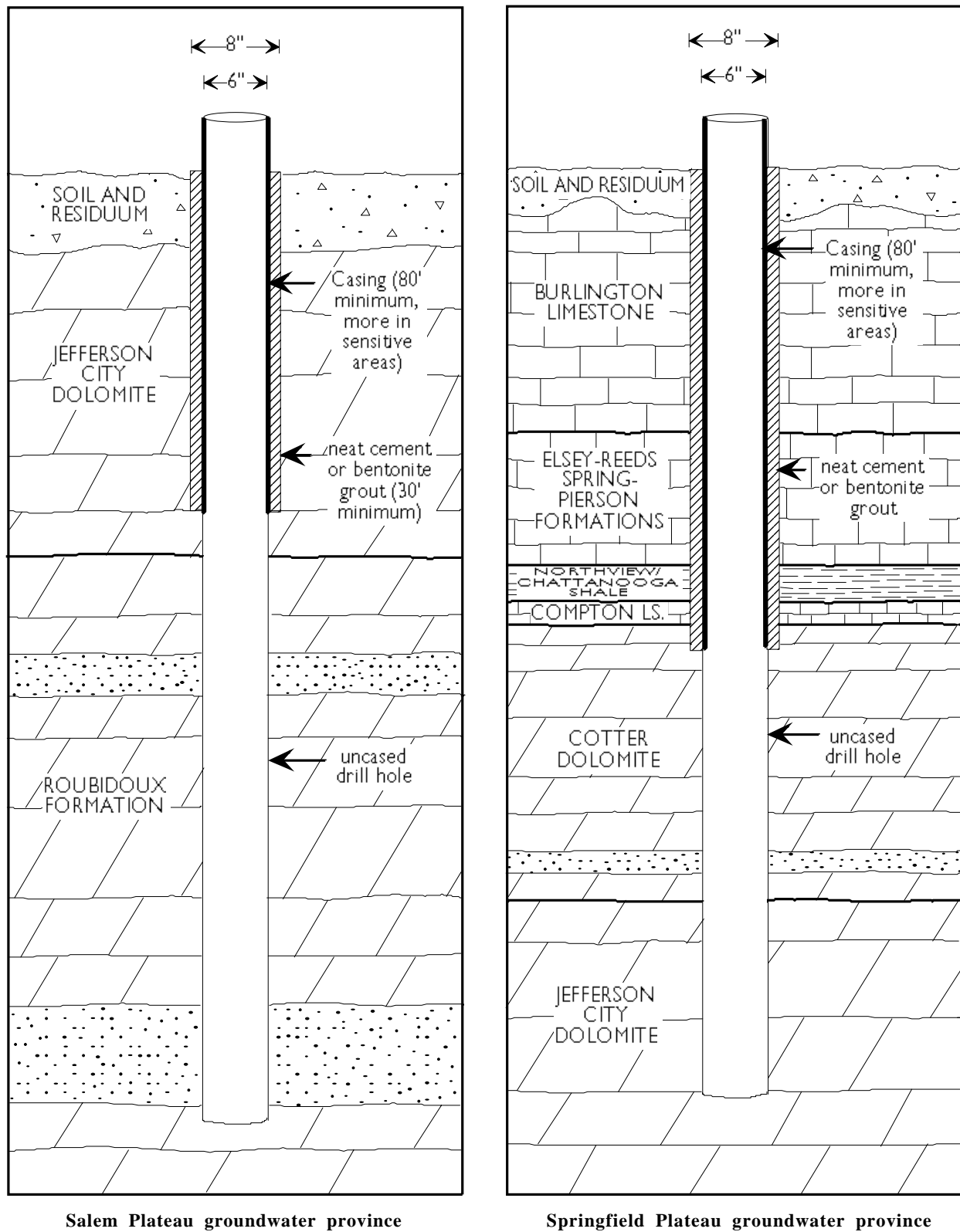


Figure 74. Typical construction of private water-supply wells in the Salem Plateau and Springfield Plateau groundwater provinces.

yield irrigation or public water supply wells may require considerably greater lengths of well screen. The screen has openings that allow water to enter the well while excluding most of the sediment. The size of the screen openings can be determined by analyzing sand samples collected from a test hole. The screen is generally sized to allow the fine particles to pass through it while the well is being developed by pumping, but will not allow most of the coarser materials to pass through it. This develops a natural gravel pack outside of the well screen. In some cases, an artificial gravel pack is used. Here, the screen is sized depending on the size of gravel or sand used for the artificial gravel pack which is placed in the well outside of the well screen. Figure 75 shows general construction of public and private wells drilled into unconsolidated alluvial materials.

Large-diameter augered wells, cased with tile or concrete casing, are typically used in the low-permeability glacial drift of northeast and northwest Missouri. These wells do not typically contain a well screen, per se. Water enters them through the small gaps between the casing joints. The inflow rates of such wells are typically less than 3 gpm, but the large diameter of the wells allows considerable water to be stored in the well bore, enough water to meet at least modest household demands (Figure 76).

WELLPLUGGING

Wells, like most man-made devices, have a useful life beyond which they either fail or require extensive repair. If repairs can be made, the useful life of the well can be extended. But if the well becomes contaminated, is no longer used, or falls into such need of repair that it is not feasible to use as a water-supply source, it should be plugged. The proper plugging of abandoned wells has always been advised when the wells are no longer needed or cannot be used, but with passage of the Water Well Drillers Act in 1985 and its revision in 1991, it is now law (RSMo 256.615).

Different types of wells require different techniques of plugging. For relatively small-diameter drilled wells such as those most commonly used throughout the state, the drill hole can be filled from the bottom to 50 ft below the casing with washed, disinfected gravel, and from 50 ft below the bottom of the casing to about 3 ft below land surface with neat cement or bentonite. The casing should be cut-off about 3 ft below ground to prevent it from interfering with surface activities. If there is more than a few feet of water standing in the well above the gravel fill, then a tremie pipe should be used to place the neat cement. Chipped bentonite can be used to fill the well if it is poured in slowly, at a rate of about one sack each three minutes, and the fine particles are removed. The above apply when the well is not contaminated by anything other than, perhaps, bacteria. More seriously contaminated wells, such as those containing organic chemicals, gasoline or other similar substances, must be plugged bottom to top with neat cement or bentonite slurry introduced through tremie pipe to ensure the contaminants will not be spread vertically through the aquifer.

Large-diameter augered or dug wells like those widely used in northern Missouri present a different type of risk. They become sites of tragedy if a child or other unsuspecting person or animal falls into an abandoned well and drowns. These wells can be plugged easily and inexpensively using a variety of materials including gravel or sand in the lower part and locally-derived clay, agricultural lime, or other inert, low-permeability material in the upper part.

Unplugged wells are a common source of groundwater contamination, and can be an expensive liability. There are numerous cases in Missouri where unplugged abandoned wells allowed groundwater contamination to occur. The plugging of wells must be viewed as an investment for the future. In many cases, the continued good quality of groundwater resources depends on it.

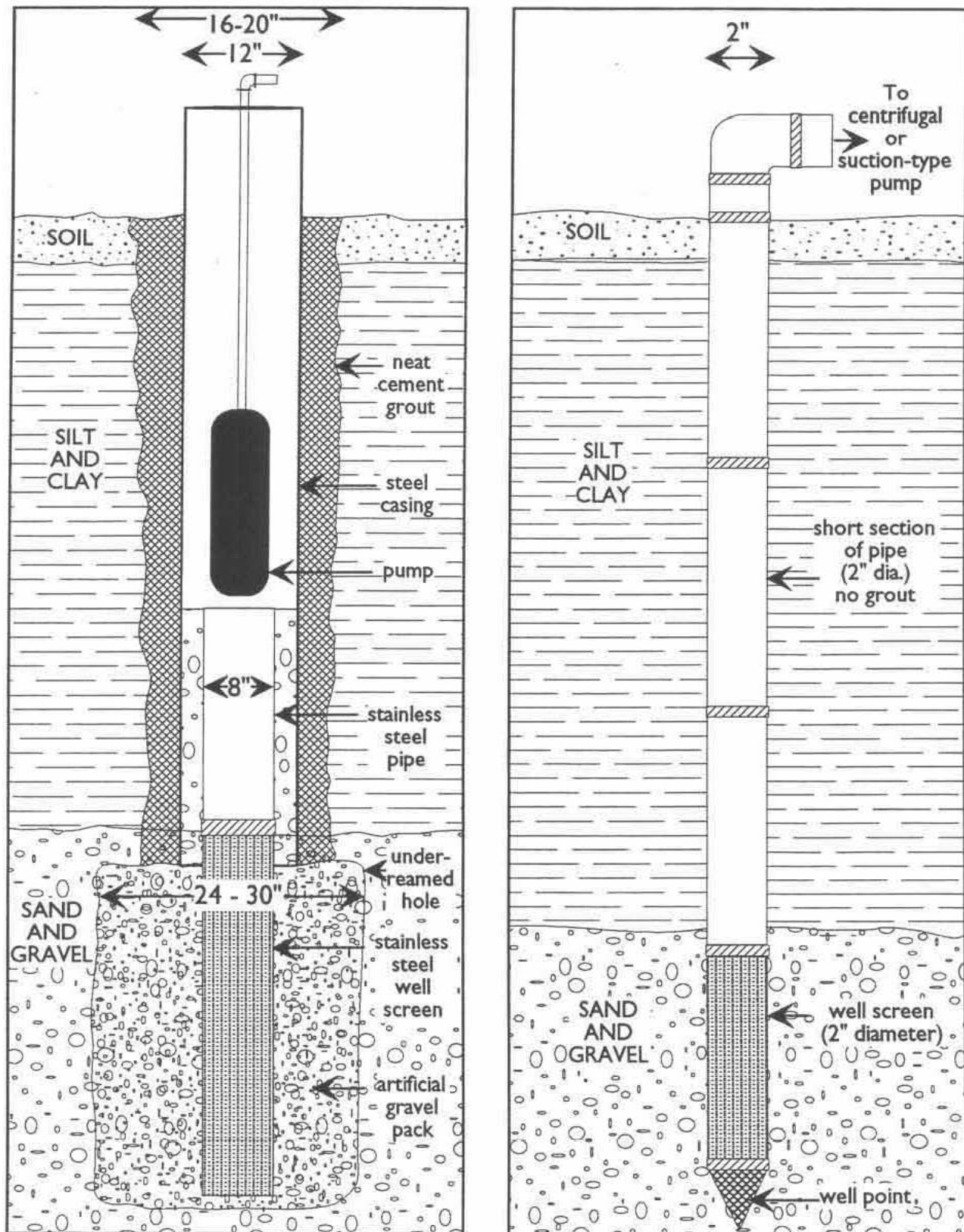


Figure 75. Typical construction used for public and private water supply wells in alluvial deposits.

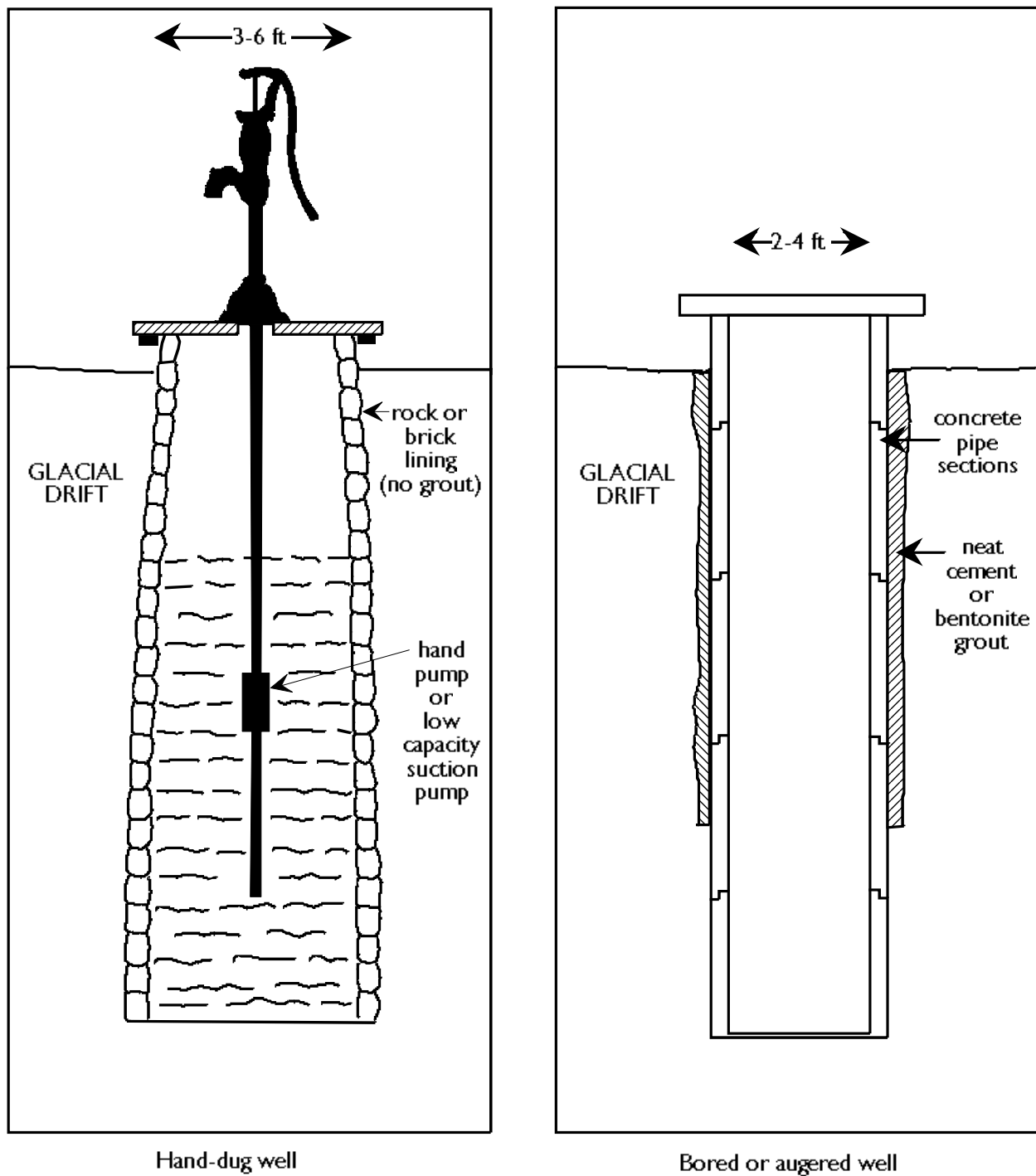


Figure 76. Typical construction used for private hand-dug and augered glacial drift wells.

SUMMARY AND CONCLUSIONS

This report is an overview of the groundwater resources of Missouri. It is not intended to be a detailed groundwater assessment or a description of site-specific groundwater problems. Rather, it is a general evaluation of the groundwater resources of a state that has very diverse, natural geologic and hydrologic conditions.

Since Missouri is so geologically and hydrologically diverse, the report divides the state into seven groundwater provinces and two subprovinces. The boundaries of the provinces are based on differences in physiography, the geologic character of the water-bearing rock formations, differences in the hydrology of the groundwater system, differences in the chemical quality of the groundwater, and the overall vulnerability of the aquifers to contamination. The provinces are the St. Francois Mountains, the Salem Plateau, the Springfield Plateau, the Southeastern Lowlands, Northwestern Missouri, Northeastern Missouri, and West-Central Missouri. The two subprovinces are the Mississippi River alluvium and the Missouri River alluvium. In each of the major groundwater provinces there may be from one to four or more aquifers.

The groundwater resource base in Missouri is one of its most important natural resources. There are more than a dozen major aquifers in Missouri whose depths vary from a few feet below land surface to more than 2,000 feet, and whose areal extents range from a few hundred square miles for localized channel sandstone deposits, to that of the Ozark aquifer,

which underlies more than 35,000 square miles of southern Missouri.

Groundwater in Missouri originates as, and is replenished by, precipitation. Shallow aquifers separated from land surface by only a few feet of relatively permeable materials receive considerable recharge very quickly after precipitation occurs. Deeper aquifers that are overlain by low-permeability strata, or aquitards, are generally recharged much more slowly. Groundwater recharge rates vary widely, from less than an inch per year in parts of northern and west-central Missouri, to more than 12 inches in certain karst areas in southeastern Missouri.

As part of this report, groundwater storage estimates were made for each of Missouri's major aquifers on a county by county basis. These estimates relied on many data sources, but basically used average saturated aquifer thickness for each aquifer within a particular county, and assumed reasonable specific yields or effective porosities. It is difficult to assess their accuracy, but the estimations are based on the best regional information available.

Missouri's greatest groundwater resources lie south of the Missouri River. The Salem Plateau groundwater province contains the greatest groundwater resources. Thick dolomite and sandstone formations of Cambrian- and Ordovician-age underlie the area, and comprise the Ozark and St. Francois aquifers. Part of the Missouri River alluvial aquifer lying south of the river is also included in this province. In the Salem Plateau groundwater

province, these aquifers contain approximately 233 trillion gallons, or about 46.6 percent of the usable groundwater in the state. The St. Francois and Ozark aquifers extend to the west into the Springfield Plateau groundwater province, where they are overlain by several hundred feet of Mississippian-age limestones that comprise the Springfield Plateau aquifer. Groundwater storage in this province is estimated to be about 122.5 trillion gallons, or about 24.5 percent of the usable groundwater in Missouri.

Considering its size, the Southeast Lowlands groundwater province contains the greatest volume of groundwater per unit area. Parts of the St. Francois and Ozark aquifers are usable in the northwestern part of this province. However, most of the groundwater is contained in thick deposits of shallow alluvium and deeper Tertiary- and Cretaceous-age sands. About 15.2 percent of Missouri's groundwater, an estimated 75.8 trillion gallons, are found in this southeastern corner of Missouri.

The remaining groundwater provinces south of the Missouri River contain more modest reserves of usable groundwater. In the St. Francois Mountains groundwater province, the St. Francois aquifer is typically the only source of appreciable quantities of groundwater except near its outer margins where the Potosi Dolomite may be thick enough to yield some water. Much of the area is directly underlain by Precambrian-age igneous rocks that are essentially impermeable and store or yield little water. This area contains less than 0.2 percent of Missouri's groundwater—an estimated 919 billion gallons.

The West-Central Missouri groundwater province fares somewhat better. The freshwater-salinewater transition zone forms the boundary between the Springfield Plateau and West-Central Missouri groundwater provinces. Aquifers in Mississippian-, Ordovician-, and Cambrian-age rock south off this transition zone yield good-quality water, but the same aquifers north of the transition zone contain highly mineralized water. The northern part of this province borders the Missouri River and includes the Missouri River alluvi-

um. Buried alluvial and glacial drift channels paralleling the river help to locally increase its groundwater resource base. Most of the area is underlain by relatively impermeable Pennsylvanian-age sedimentary strata that yield, at best, only meager volumes of marginal quality water. Groundwater storage estimates for this region are about 1.2 trillion gallons, or about 0.24 percent of the usable groundwater in Missouri. Cumulatively, the groundwater provinces south of the Missouri River contain about 86.7 percent of the states usable groundwater.

The remaining 13.3 percent of Missouri's groundwater occurs in the northern part of the state. In the Northwestern Missouri groundwater province, the alluvial deposits along the Missouri River and thick glacial materials form its most significant aquifers. This area contains an estimated 10.9 trillion gallons of groundwater, or about 2.2 percent of the groundwater in Missouri. Deeper bedrock aquifers contain vast quantities of water, but the water is too highly mineralized to be considered potable.

Groundwater resources in the Northeastern Missouri groundwater province are much more varied. Glacial drift also underlies much of this area, but is generally thinner and finer-grained than in northwest Missouri. Alluvial deposits bordering the Missouri and Mississippi rivers are important aquifers. Mississippian-age limestones yield modest amounts of marginal quality water in the northern part of the region, while south of the freshwater-salinewater transition zone, Mississippian, Ordovician, and Cambrian limestones, dolomites, and sandstones are important aquifers. This province contains about 11.1 percent of Missouri's potable groundwater, a volume of about 55.8 trillion gallons.

Figure 77 graphically depicts potable groundwater storage estimates for each county in the state. As can be seen by the illustration, there are large differences in groundwater storage volumes between counties and between groundwater provinces. Many of the northern and west-central Missouri counties and several in the St. Francois Mountains have relatively poor groundwater resources. How-

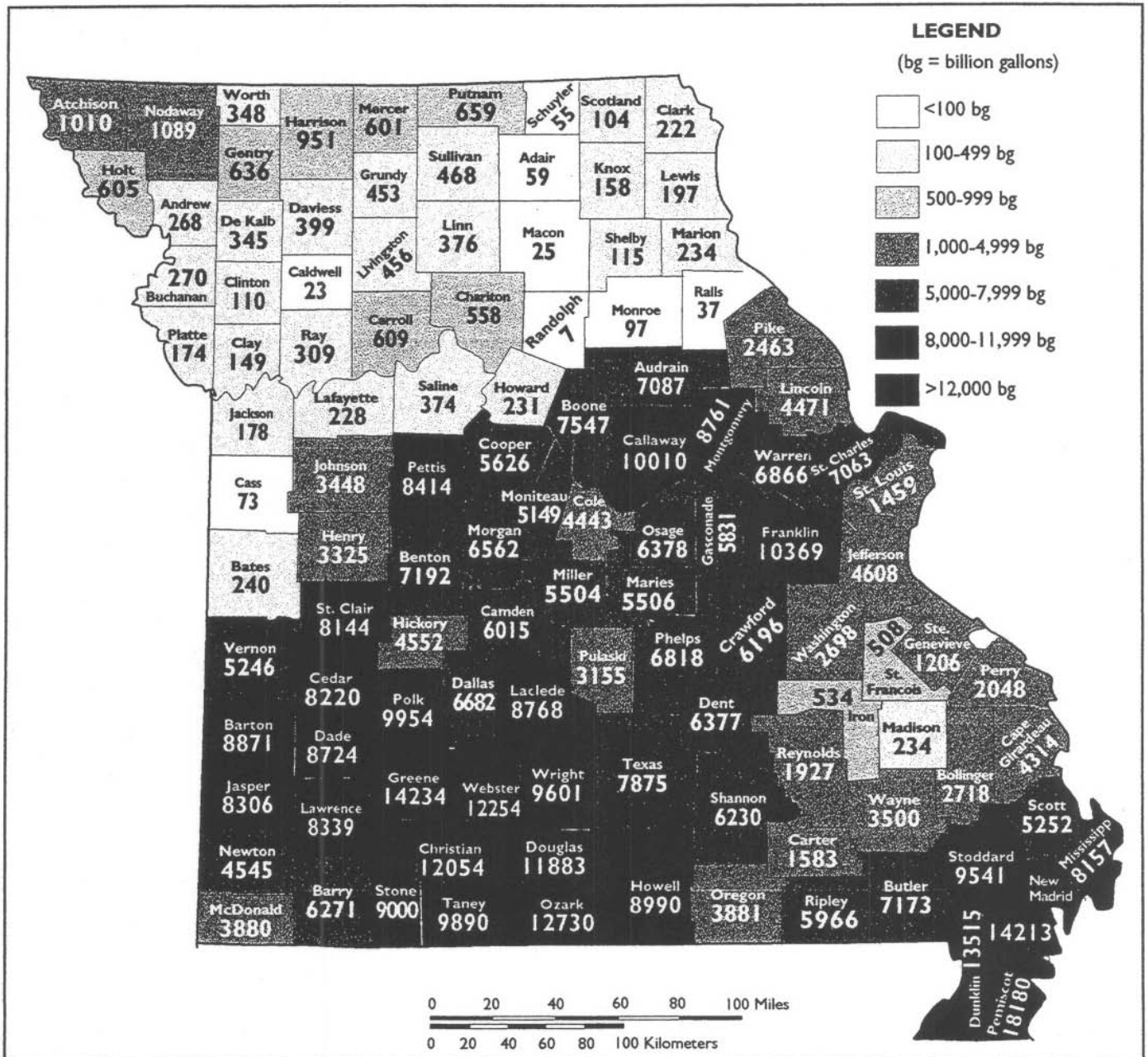


Figure 77. Potable groundwater storage by county for Missouri.

ever, there are probably no places in Missouri where the groundwater resources, when combined with surface water resources, cannot meet water demands.

Statewide groundwater storage estimates show that aquifers in Missouri contain slightly more than 500 trillion gallons of usable quality groundwater. This is enough water to cover the state to a depth of over 34 feet, or supply each of its 5.1 million residents 100 gallons of water per day for nearly 2,700 years. It is equivalent to the volume of rainfall that Missouri normally receives in nearly an 11-year period. The above comparisons are useful for visualizing the magnitude of this resource, but do not reflect how groundwater should be managed. For example, a per capita water use of 100 gallons per day is commonly assumed when estimating water use for small towns, public water supply districts, and even private water supplies. But this is but a small fraction of the total amount of water needed for our society. Tremendous volumes of water are used for industrial and commercial purposes, agricultural irrigation, power production and other purposes. It must be remembered that in order to remain a renewable resource, the net use of groundwater must not exceed its net recharge.

The volume of groundwater that Missouri has available is so staggering that it is difficult to imagine how such a resource could ever be depleted. In a few areas of the state it would be extremely difficult to use all of the available groundwater. However, groundwater resources are not evenly distributed. Neither is groundwater use. Production from a particular aquifer may be minimal throughout most of a county, but very high in a few square-mile area due to municipal, industrial or agricultural needs. It is quite possible to overuse an aquifer in one area, while the same aquifer a few miles away is essentially unused.

A commonly asked question is how much water can be safely removed from a particular aquifer? Unfortunately, such a question is much more easily asked than answered. Ideally, the volume of water in Missouri aquifers should be kept relatively constant. If

more water is removed from the aquifer than is replenished by recharge, groundwater levels begin to decline. As depth to groundwater increases, the costs of new well construction increases because wells will need to be drilled deeper. Existing wells may have to be deepened and equipped with larger pumps, and pumping costs will increase because the water is being pumped against a greater head pressure. Todd (1959) defined the *safe yield* of a groundwater basin as the amount of water that can be withdrawn from it annually without producing an undesired result. Any withdrawal in excess of safe yield is termed an *overdraft*. An undesired result could be a decline in groundwater level, a change in water quality, or other consequence. Groundwater overdrafts can generally be tolerated only when they are a short-term occurrence. For instance, groundwater overdrafts often occur during extended droughts when heavier than normal demands are placed on groundwater resources. This is probably acceptable so long as groundwater levels are allowed to recover when precipitation returns to normal levels.

Driscoll (1987) states that the wise use of groundwater involves three general principles: (1) development of technologies that will enhance the storage capacity of groundwater reservoirs, (2) protection of groundwater quality, and (3) utilization of groundwater resources for their highest or most valuable use to society. Private water-supply users, farmers, cities and others can probably do little about the first of the above principles, although considerable research has been conducted on enhancing aquifer storage capacity, improving well yields, and replenishing aquifers through artificial recharge. Existing state and federal laws have done much to address the second principle. All users of water should seriously consider the third factor before deciding on a water supply source. If their water-use demands will appreciably affect groundwater levels or cause other undesired changes in the aquifer, then it would be prudent for them to explore other water-supply options.

A sizeable percentage of Missouri's usable groundwater is in aquifers that are relatively expensive to exploit. For example, the St. Francois aquifer in the St. Francois Mountains area is fairly shallow. However, in southwestern Missouri it may be more than 2,000 ft in the subsurface. So, even though it is considered a groundwater resource, it is mostly unused because shallower, more productive aquifers are available throughout much of the Ozarks.

If groundwater resources were evenly distributed across the state, then each square mile of Missouri would contain about 7.17 billion gallons of water beneath it. Unfortunately, this is not the case. Average groundwater availability in Missouri north of the Missouri River is only about 2.8 billion gallons per square mile, while that of the southern part of is much higher, about 9.5 billion gallons per square mile. Locally, groundwater storage in northern Missouri can be much less than the average. Thus, a resource that many take for granted in the southern part of the state is considered a precious commodity in the north.

Another factor to consider is that the quality of water is a most important consideration in determining its potential use. Groundwater contamination due to improper waste disposal, inappropriate land use, accidental spills, and other factors can cause a usable aquifer to essentially become unusable, at least for an extended period of time.

Although groundwater is a vast resource in Missouri, it is also a finite resource. Unlike

many western states where groundwater recharge rates are so low that groundwater is not replenished, many Missouri aquifers receive considerable recharge during most years. With proper management and protection, Missouri's groundwater resources can continue to provide high-quality water to meet many of Missouri's domestic, municipal, industrial, agricultural, and recreational needs. Avoiding aquifer over-use and protecting groundwater from contaminants are two ways to best ensure its continued availability for future generations.

Missouri statutes and regulations generally provide for adequate protection of water quality. However, there are few if any laws that regulate the volume of water that is used for a particular purpose. (For a more complete assessment of water law in Missouri, the reader is referred to *Missouri Water Law, Missouri State Water Plan Series Volume VII* [Gaffney and others, 1998]). If groundwater use exceeds recharge, water-level declines will occur, and disputes will likely arise. Currently, these types of disputes, though uncommon, must be addressed in the courts through civil suits. As population and water use increases, there will be even greater demands placed on groundwater resources, and the incidence of water-use conflicts will probably increase. Further legislation may be needed in the future to prevent overuse of groundwater resources, or to define which uses should receive priority, especially during periods of drought or where groundwater demands greatly exceed resource capacity.

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Well Owner	County	Location Sec. T. R.	Yield (gpm)	Transmissivity gal/day/ft	Storage Coefficient (dimensionless)
Lost Valley Hatchery Well #1	Benton	04 40N 22W	450	4,604	1.6×10^{-4}
City of Camdenton Well #6	Camden	25 38N 17W	500	3,568	NA
Church Farm #7	Cole	18 45N 12W	100	573	2.0×10^{-4}
Cole Co. PWSD #1 Well #3	Cole	18 44N 12W	570	16,217	1.6×10^{-3}
MO State Penitentiary Well #2	Cole	08 44N 11W	260	5,280	1.5×10^{-3}
City of Cuba Well #4	Crawford	30 39N 04W	300	7,900	1.0×10^{-3}
City of Buffalo Well #2	Dallas	23 34N 20W	350	6,160	1.5×10^{-3}
Dent Co. PWSD Well # 1	Dent	29 34N 05W	150	1,460	NA
City of Sullivan Well #10	Franklin	10 40N 02W	200	2,400	NA
City of Union Well #2	Franklin	27 43N 01W	608	34,151	NA
City of Hermann Well #3	Gasconade	26 46N 05W	350	1,270	3.0×10^{-3}
City of West Plains Well #8	Howell	18 24N 08W	420	2,464	NA
Jefferson Co. PWSD #7 Well B	Jefferson	26 41N 04E	323	101,000	6.6×10^{-3}
Laclede Co. PWSD #1 Well #3	Laclede	12 33N 17W	140	3,800	2.0×10^{-4}
Laclede Co. PWSD #3 Well #6	Laclede	07 33N 18W	225	2,970	NA
City of Belle	Maries	21 41N 07W	145	2,000	1.0×10^{-3}
Ozark Co. PWSD #1	Ozark	18 22N 15W	150	5,800	2.0×10^{-3}
Tyson Foods Well #2	Pettis	22 46N 22W	950	7,838	2.0×10^{-3}
Rolla Industrial Park Well #2	Phelps	32 38N 07W	500	19,000	9.0×10^{-9}
City of St. James Well #4	Phelps	19 38N 06W	550	12,000	2.5×10^{-4}
City of Rolla Well #13	Phelps	07 37N 07W	802	13,233	NA
Ft. Leonard Wood Well #2	Pulaski	09 35N 11W	200	2,640	NA
Ft. Leonard Wood Well # 8	Pulaski	04 35N 11W	250	1,375	1.2×10^{-4}
Eastern MO Corr. Fac. Well #2	St. Louis	05 43N 03E	350	27,600	NA
Texas Co. PWSD #1 Well #2	Texas	27 33N 11W	180	2,500	NA
City of Licking Well #3	Texas	07 32N 08W	300	4,300	3.0×10^{-4}
Cabool Industrial Park	Texas	10 28N 11W	200	4,800	4.0×10^{-3}